

To the Graduate Council:

I am submitting herewith a dissertation written by Patrick J. Steffanic entitled “Pion, Kaon, and Proton Production in Jet-Hadron Correlations from Pb-Pb Collisions at $\sqrt{s_{NN}}=5.02$ TeV Using the ALICE Detector.” I have examined the final paper copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Physics.

Christine Nattrass, Major Professor

We have read this dissertation
and recommend its acceptance:

Christine Nattrass

Nadia Fomin

Miguel Madurga

Hairong Qi

Accepted for the Council:

Dixie L. Thompson

Vice Provost and Dean of the Graduate School

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(Original signatures are on file with official student records.)

**Pion, Kaon, and Proton
Production in Jet-Hadron
Correlations from Pb-Pb Collisions
at $\sqrt{s_{NN}}=5.02$ TeV Using the
ALICE Detector**

A Dissertation Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Patrick J. Steffanic

August 2024

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To Mark Womack, who set me on this quest with some scribbles on the back of a crumpled sheet of paper at lunch. His empathy for others and genuine curiosity have inspired me and dramatically shaped the way I live my life.

To Dr. Jennifer Klay, who accepted a very confident freshman into her research group and taught me how to be a scientist and a good person. Her advice and guidance have opened opportunities for me that I never thought would be possible.

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Sometimes you eat the bear, and sometimes, well, he eats you.

—*The Stranger, The Big Lebowski*

If you don't take risks, you can't create a future!

—*Monkey D. Luffy, One Piece*

Abstract

Interactions between hard probes and the quark-gluon plasma (QGP) are a rich probe of the dynamics of the QGP. In this thesis, we study the production of pions, kaons and protons from jet-hadron correlations in 0-10% and 30-50% central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the ALICE detector at the LHC. We focus our studies on low momentum jets with $20 \text{ GeV}/c < p_T^{\text{jet}} < 40 \text{ GeV}/c$ using associated hadrons with $1 \text{ GeV}/c < p_T^{\text{assoc.}} < 10 \text{ GeV}/c$. The yields of associate pions, kaons and protons were measured in the near-side and away-side regions of the jet-hadron correlation function, and the baryon to meson and strange to non-strange meson ratios were computed. This is the first measurement of the strange to non-strange meson ratio for hadrons associated with a jet. We find the baryon to meson ratio for associated hadrons in Pb-Pb collisions to be within uncertainty of the ratio for inclusive charged hadrons in proton-proton collisions. The strange to non-strange meson ratio for associated hadrons in Pb-Pb collisions shows strong enhancement at intermediate $p_T^{\text{assoc.}}$ relative to the ratio for inclusive charged hadrons in proton-proton collisions, with a hint of enhancement over the ratio for inclusive charged hadrons in Pb-Pb collisions. We find that the enhancement is larger for hadrons associated with the away-side region relative to those associated with the near-side region, and that the effect is larger for 0-10% central collisions than for 30-50% central collisions. These findings suggest that the strangeness enhancement of associated hadrons is driven by interactions between the jet and the medium, and may provide insight into the path-length dependence of jet-medium interactions in heavy-ion collisions. We hope that future comparisons to

simulations and other measurements will provide further insight into this unexpected enhancement.

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Chapter 1

Introduction

Heavy-ion collisions are a powerful tool for studying quantum chromodynamics (QCD) and the properties of the strong force. They provide the necessary conditions for the formation of a new form of matter called the quark-gluon plasma (QGP). The formation of a QGP in heavy-ion collisions has been demonstrated exhaustively over the years [1, 2, 3, 4]. Jets, columnated sprays of hadrons originating from a hard parton scattering, are an excellent probe of the QGP [5, 6]. Hard parton scatterings occur early on in the collision and traverse varying amounts of QGP, resulting in energy loss in the medium. Precision measurements of energy loss for jets in heavy-ion collisions have been made at the Large Hadron Collider (LHC) [6] and the Relativistic Heavy Ion Collider (RHIC) [7]. Shower dynamics for partons from a hard scattering in a dense medium are not well understood, but some measurements help constrain the modifications to the parton shower. Measurements of charged hadrons show significant baryon and strangeness enhancement in heavy-ion collisions relative to proton-proton collisions [8]. This enhancement has generally been understood to be due to recombination, an alternative hadronization mechanism proposed for heavy-ion collisions [9]. Interactions between jet partons and the medium could drive similar enhancements in jet constituents. Several measurements of the baryon-to-meson ratio in jets show no difference between jet constituents in heavy-ion and proton-proton

collisions [10, 11, 12, 13] within large uncertainties. However, some jets will experience more QGP, leading to greater modification of their hadrochemistry as hinted at in [12, 14, 15]. In this thesis, we extend this work by measuring the kaon-to-pion and proton-to-pion ratios for jets in lead-lead and proton-proton collisions at $\sqrt{s}=5.02$ TeV. We see no evidence of baryon enhancement for jets in heavy-ion collisions relative to proton-proton collisions or between jets experiencing different amounts of QGP. We do see some evidence of strangeness enhancement for jets relative to proton-proton collisions and inclusive charged hadrons in heavy-ion collisions. However, the significance of this enhancement is limited by the size of the uncertainties, and some kinematic biases have not yet been fully evaluated.

1.1 Quantum Chromodynamics

Quantum chromodynamics is the mathematical theory governing the strong interaction, whose fermions are the six quarks, mediated by the eight gluons. Each quark has a color charge, either red, green, or blue, and gluons, which also carry color charge, mediate interactions between pairs of color charges. The strength of the strong force varies depending on the length scale of the interaction. Unlike photons, which are electrically neutral, gluons strongly interact with each other. Because of this, QCD matter exhibits two unique properties, confinement and asymptotic freedom. Quarks are almost always bound in hadrons, comprising either two or three quarks, called mesons and baryons, respectively. The gluons binding the quarks form flux tubes with constant energy density [16]. As the quarks are drawn apart, more energy is stored in this flux tube, and eventually a new quark-antiquark pair is produced. This inability to separate a bare quark from a hadron is called confinement. At higher energies, or shorter length scales, the strong force becomes weaker. This is called asymptotic freedom [17], and allows for the use of perturbative methods in QCD calculations. A direct comparison of experimental data and theoretical calculations can be undertaken in such cases.

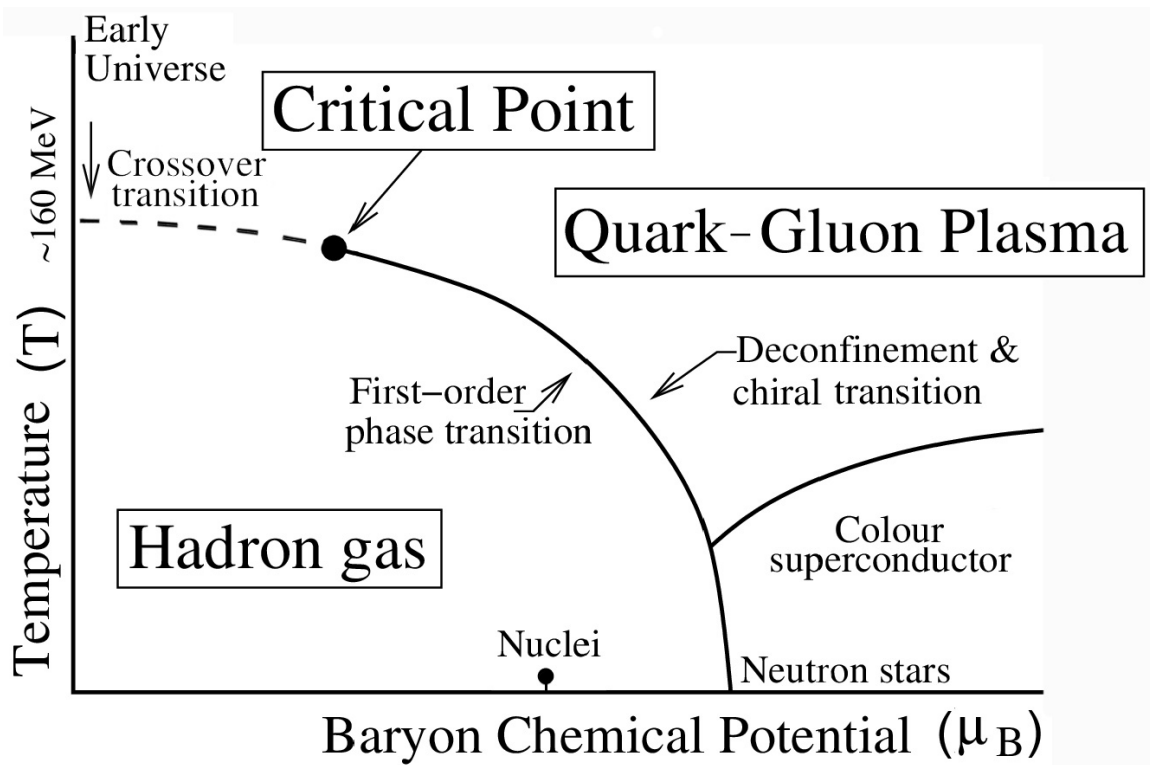


Figure 1.1: The QCD phase diagram [26].

1.2 Quark-Gluon Plasma

Hagedorn [18] introduced the notion that there may be a theoretical highest temperature at which hadrons can exist. Cabibbo and Parisi [19] showed that Hagedorn's model could be understood as either implying a limiting temperature, or a second order phase transition. It is presently understood that the Hagedorn temperature is the temperature of the phase transition from hadrons to a new form of matter called the quark-gluon plasma. Since these proposals, myriad evidence has been gathered supporting the existence of a QGP [20]. It has been theorized that the early universe was composed of a QGP, and we know that a droplet of QGP is formed in heavy-ion collisions at the LHC and RHIC. The QCD phase diagram is shown in Figure 1.1. At high temperatures and densities, a phase transition has been observed from confined, hadronic QCD matter to a deconfined QCD matter called the QGP. The QGP forms above temperatures around 156 MeV [21] and has a minimum energy density of around $1 \text{ GeV}/fm^3$ [22], though it can be greater than $10 \text{ GeV}/fm^3$ at LHC energies [23]. Under these extreme conditions, quarks and gluons move and interact freely with each other, quickly realizing a thermal and baryochemical equilibrium for light quarks and gluons and partial equilibrium for strange quarks, depending on the collision centrality [24]. Remarkably, the QGP behaves like a perfect liquid, which is a fluid with zero viscosity [25].

Both short- and long-distance interactions are significant in the QGP. For short-distance interactions, perturbative techniques can be used. Long-distance interactions require phenomenological descriptions and nonperturbative methods such as lattice QCD. Phenomenological techniques require assumptions about the mechanisms of the QGP that do not directly arise from QCD, but are successful in describing the experimental data. Lattice QCD is a discretized field theory that recovers continuum QCD in the infinite lattice, infinitesimal lattice spacing regime /citeLatticeQCD. The finite lattice spacing introduces a natural momentum cutoff that regularizes QCD on the lattice. Comparing measurements in heavy-ion collisions with theoretical

predictions continues to sharpen our understanding of the processes at play in the QGP.

1.3 Heavy-Ion Collisions

Heavy-ion collisions create the conditions necessary for the formation of a droplet of QGP. Heavy-ion collisions undergo several stages starting from the moments before the collision to the final state particles measured by our detectors. A light-cone diagram of a heavy-ion collision is shown in Figure 1.2 demonstrating the different stages. At time t_0 , the two incoming nuclei collide as Lorentz-contracted disks. Approximately 1 fm/c later, the QGP forms in the central region between the receding nuclei. The QGP expands and cools, driven by the enormous pressures of the collision, until it reaches the first freeze-out temperature, T_c . At this point a hadron gas, consisting of interacting hadrons but not free quarks or gluons, begins to form. The hadron gas continues to cool until chemical interactions between the hadrons cease at the chemical freeze-out temperature, T_{ch} , fixing the hadron fractions. Finally, the hadron gas continues to cool until thermal interactions between the hadrons cease at the thermal freeze-out temperature, T_{fo} , fixing the momenta and energies of the hadrons.

1.3.1 Initial State

Figure 1.3 shows a diagram of the initial geometry in a heavy-ion collision. The impact parameter, b , is the distance between the centers of each incoming nucleus and determines the centrality of the collision. Centrality describes the overlap between the two colliding nuclei as a percentile of the multiplicity, or number of particles, in the collision. A head on collision corresponds to 0% centrality with the highest multiplicity and a very peripheral collision corresponds to 100% centrality with the

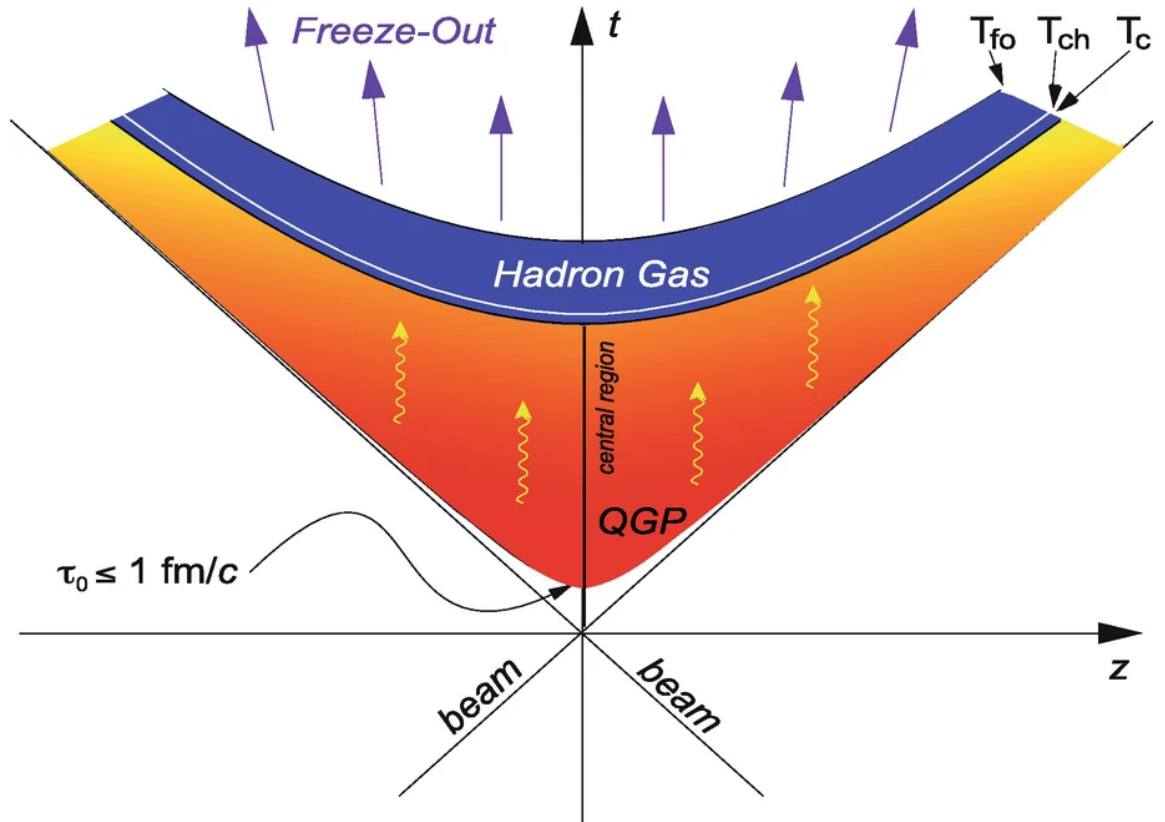


Figure 1.2: A light-cone diagram of a heavy-ion collision showing the different phases of the collision [27].

lowest multiplicity. In practice, the impact parameter cannot be measured, and the event multiplicity is used to estimate event centrality.

In addition to the geometric overlap, fluctuations in the positions and momenta of the nucleons are important for characterizing collisions. The spatial fluctuations can be described by the Glauber model, though other more sophisticated models like Trento [28] can be used instead. The Glauber model distributes nucleons randomly in the nucleus according to a Woods-Saxon distribution [29] in the transverse plane and following a straight trajectory along the beam direction. Figure 1.4 shows an example of a randomly generated lead-lead collision.

The momentum fluctuations are described by the nuclear parton distribution function(PDF). The nuclear PDF describes the momentum distribution of each parton in the colliding nucleus. The nuclear PDF differs from the PDF used in proton-proton collisions because partons in a nucleus are bound in nucleons [30]. The PDFs for nuclei and protons are shown in Figure 1.5 demonstrating the dynamic nature of a hadronic system. While on-shell valence quarks make up a majority of the high energy partons, as we move to lower energies, gluons dominate. This phenomena is referred to as gluon saturation and is one of the major topics that will be studied with the upcoming electron-ion collider [31]. Spatial fluctuations in the beam direction and momentum fluctuations in the transverse direction can usually be ignored because the incoming nuclei are boosted into very thin Lorentz-contracted disks.

1.3.2 QGP Formation and Hydrodynamic Evolution

As the incoming nuclei begin to overlap, most of the interactions between partons are soft. These interactions produce longitudinal color fields that fill the space between two outgoing nuclei. At high enough collision energies like those at RHIC and the LHC, the energy density in this region is much larger than that of a hadron, exceeding the Hagedorn temperature. Therefore, a QGP is produced in the overlap region in

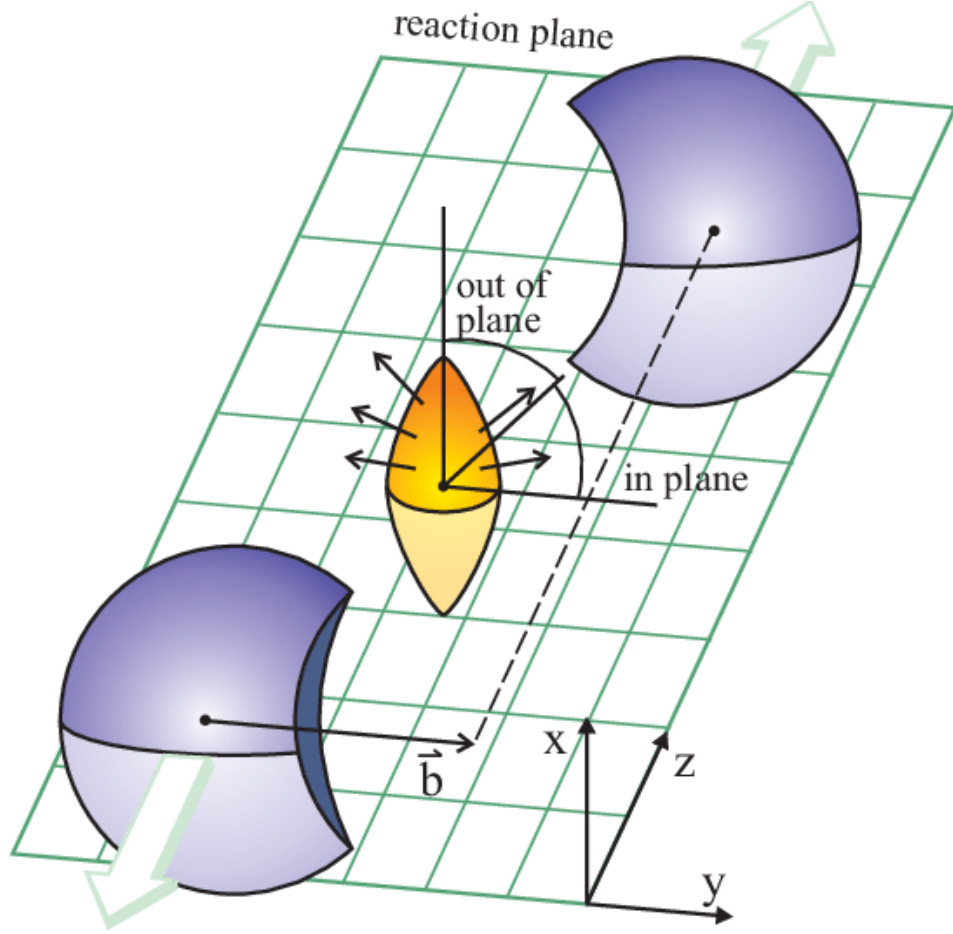


Figure 1.3: The initial geometry of a heavy-ion collision [33]. The QGP is formed in the central overlap region, and pressure gradients drive momentum anisotropies along the reaction plane.

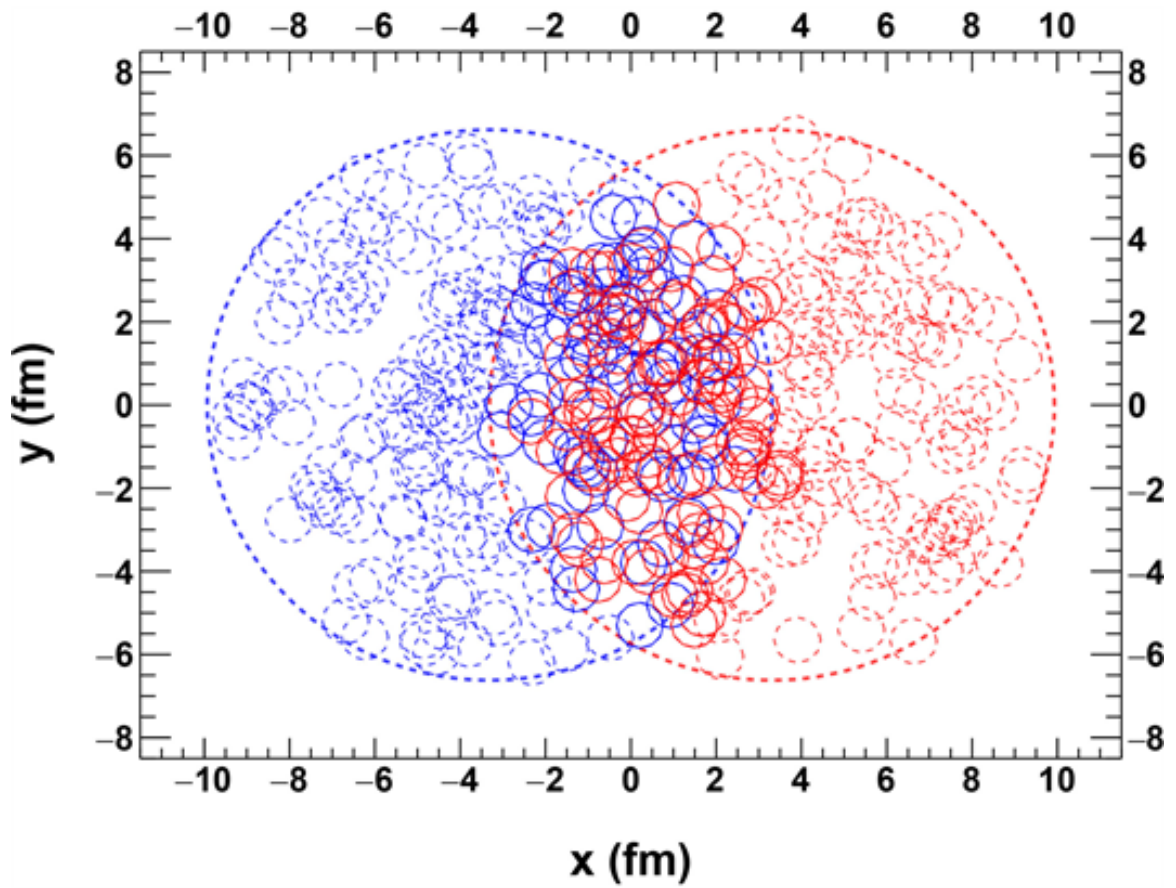
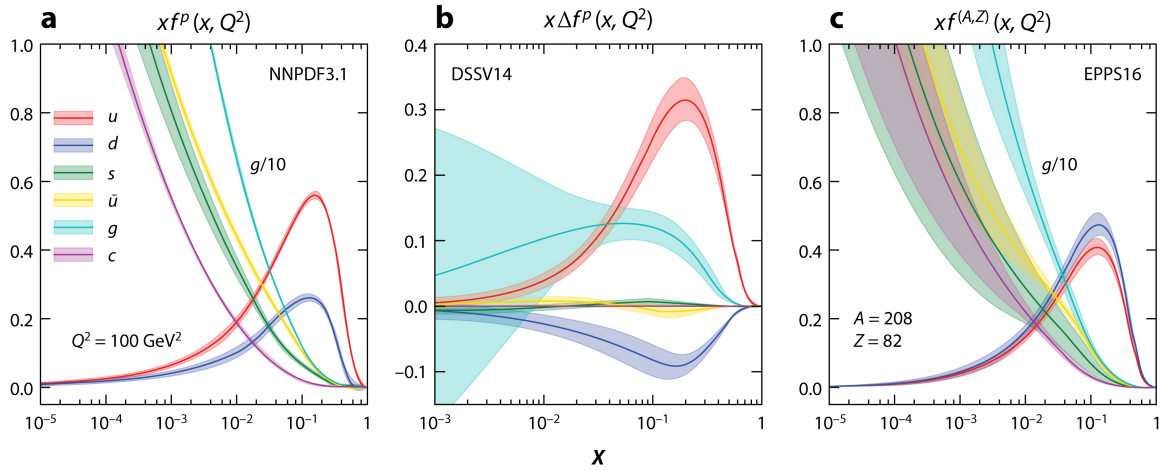


Figure 1.4: A collision between two randomly generated lead nuclei with an impact parameter of 6.62 fm, projected onto the transverse plane. [34]



 Ethier JJ, Nocera ER. 2020.
Annu. Rev. Nucl. Part. Sci. 70:43–76

Figure 1.5: The nuclear parton distribution functions for (a) unpolarized and (b) polarized protons, as well as (c) lead collisions. [30]

approximately 1 fm/c, with the subsequent lifetime of the QGP being approximately 10 fm/c [32].

The evolution of the QGP can be described as a nearly perfect, strongly-interacting fluid [35]. Pressure gradients imparted from the initial states of the colliding nuclei drive the expansion of the QGP, which is described by relativistic hydrodynamics [35]. The QGP has the lowest measured viscosity to entropy ratio of any known fluid [36]. The expansion manifests as a momentum anisotropy in the final state hadrons relative to the participant planes, where the second-order participant plane is an approximation of the reaction plane. This anisotropy is called flow and is characterized by a Fourier series [37],

$$\frac{dN}{d(\phi - \Psi_{EP})} \propto 1 + 2 \sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_{EP})) \quad (1.1)$$

where N is the number of particles, ϕ is the azimuthal angle of the particle, Ψ_{EP} is the event plane angle, and v_n are the flow coefficients.

The v_n can each be ascribed to particular geometries of the collision and are governed by the initial state geometry of the colliding nuclei. Elliptical flow, v_2 is greatest in semi-central collisions where the nuclei have a roughly 50% overlap. Triangular flow, v_3 , is driven by fluctuations of the nucleon positions in the colliding nuclei. The flow coefficients have been measured for charged hadrons [38], identified hadrons [39], and jets [40], as well as J/Ψ , heavy-flavor, and other final state particles. The flow coefficients for identified hadrons are shown in Figure 1.6. A key result is the mass ordering below 2 GeV/c. The flow coefficients for pions are greater than those for kaons, which are greater than those for protons. This phenomenon has been studied and it has been found that scaling v_2 and p_T by the number of constituent quarks in each hadron results in a nearly universal curve [41]. This can be seen in Figure 1.7 where the universality is even more evident when considering transverse kinetic energy over p_T . This has been interpreted as indicating that quarks flow in the medium, not hadrons.

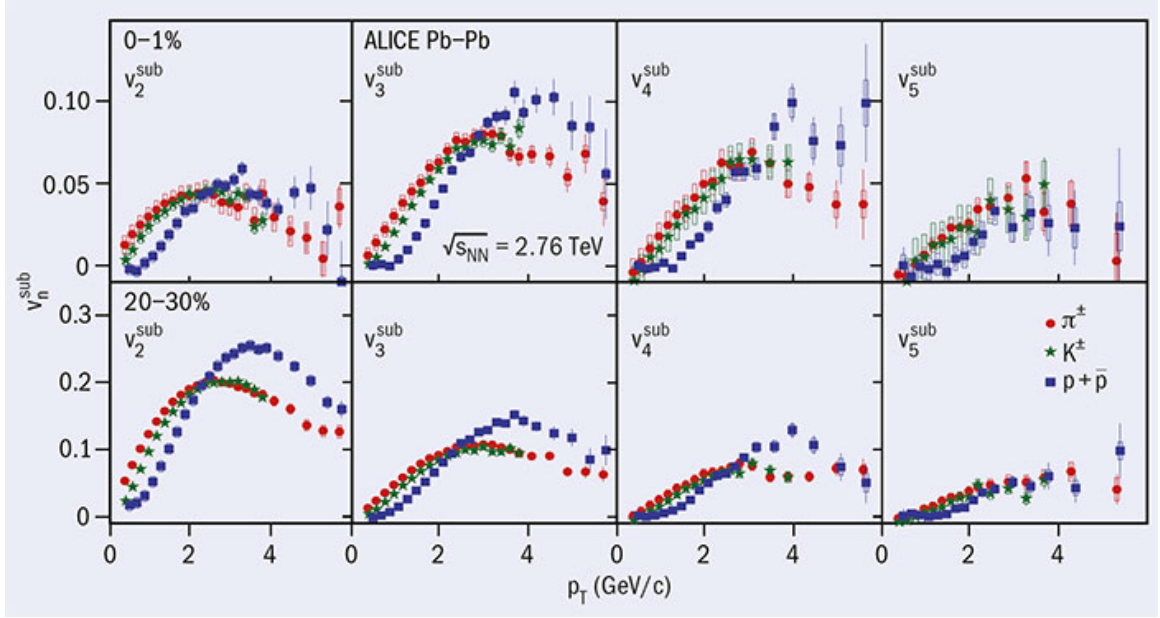


Figure 1.6: The flow coefficients v_n for pion, kaons, and protons [39]. The mass-ordering at low momentum can be clearly seen in the difference between protons and pions. The difference is much less prominent between kaons and pions. This is a consequence of quarks, rather than hadrons, flowing.

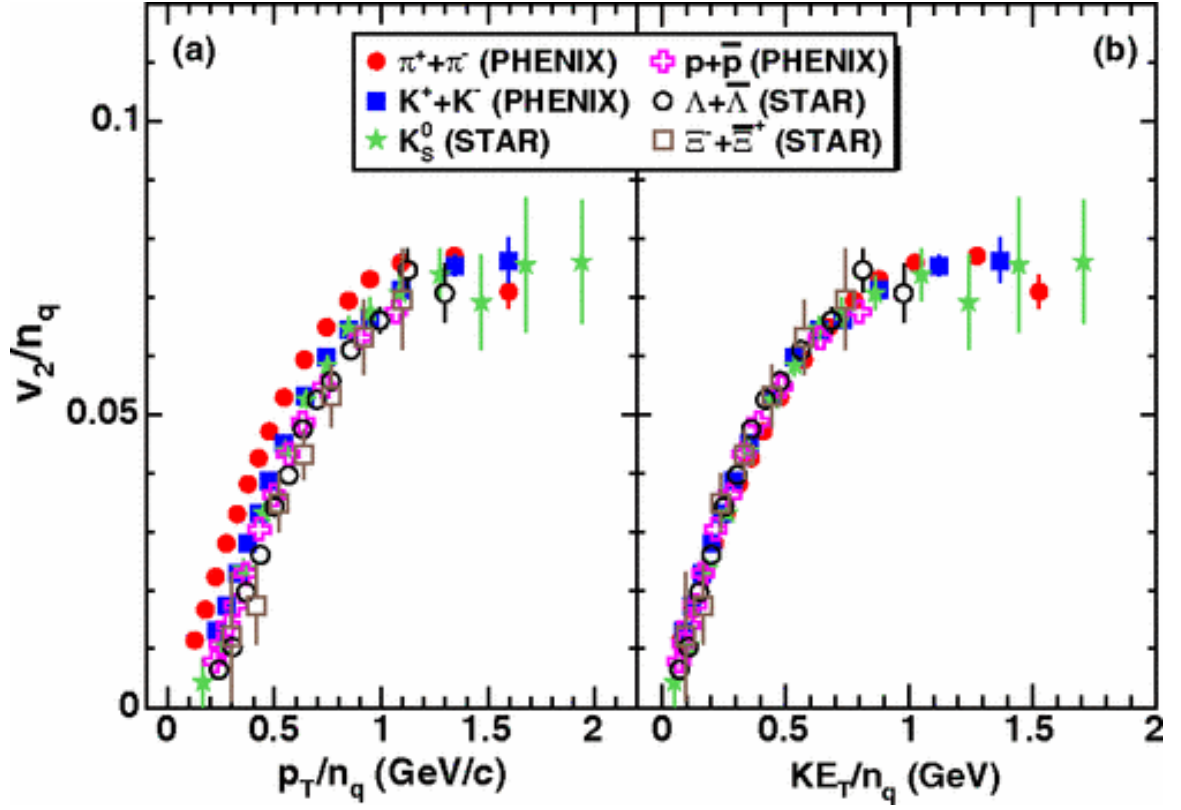


Figure 1.7: The v_2 scaled by number of quarks for pions, kaons, protons, lambdas and Ξ s [41].

1.3.3 Hadronization

As the QGP expands and cools it reaches a density and temperature at which a hadron gas is formed. In the hadron gas phase, hadrons interact chemically, changing the fractions of each hadron species, and kinetically, changing the energy of each hadron. The transition from a QGP to a hadron gas is a process called hadronization, which is the formation of hadrons from free quarks and gluons via fragmentation and recombination [9]. Fragmentation is the dominant mechanism for hadronization in jets and high- p_T hadrons. It is characterized by the fragmentation function, $D_{i \rightarrow h}(z)$, which describes the probability of a parton i fragmenting into a hadron h with a fraction z of the parton's momentum. Alternatively, in a densely populated color field, two or three quarks which are close by in phase space may form a meson or baryon, respectively. This process is called recombination and may be responsible for the large enhancement of baryons in heavy-ion collisions relative to proton-proton collisions. To produce a baryon via fragmentation, the fragmenting parton must have at least twice the mass energy due to approximate baryon number conservation. Producing a baryon by recombination requires only three quarks are nearby in phase space which carry one third the energy of the resulting baryon. The requirement that the quarks be nearby in phase space could have implications for the hadronization of jets in the QGP because the jet partons are very far away in momentum space even if they are spatially close to medium partons.

Studies of the formation of deuteron in jets in proton-proton collisions suggest that recombination is a relevant mechanism in proton-proton collisions [42]. Fragmentation in heavy-ion collisions can be modified relative to proton-proton collisions through energy loss and flavor change interactions. The formation of a QGP in heavy-ion collisions results in a large energy density in the collision region, which makes recombination more likely, though the degree to which it is enhanced is unclear. The interplay between fragmentation and recombination in the presence of a QGP can lead to enhancement or suppression of different hadron species in the final state.

1.3.4 Chemical and Thermal Freeze-Out

Shortly after the formation of a hadron gas, chemical interactions between the hadrons cease, freezing the hadron fractions. This occurs at the chemical freeze-out temperature, T_{ch} [43, 1, 44]. The hadron gas continues to expand and cool, eventually reaching the thermal freeze-out temperature, T_{fo} , where collisions between hadrons cease and their momenta and energies are fixed. At this point, final state hadrons stream freely into the detectors.

1.4 Jets

Early on in the collision, quarks and gluons sometimes scatter off each other transferring a large amount of momentum in the process. The products of these scatterings fragment into collimated sprays of hadrons called jets. The dominant process contributing to the cross-section of hard interactions is the $2 \rightarrow 2$ process. This is because the energy scale of the interaction is large and so the coupling constant is small, suppressing higher order processes. As a result, jets are almost always found in pairs 180° away in azimuth due to momentum conservation since the incoming partons have very little momentum in the transverse plane. Jets in heavy-ion collisions lose energy relative to the jets formed in proton-proton collisions due to modifications by the QGP [6]. Therefore, by studying jets formed in heavy-ion and proton-proton collisions, we can better understand the properties of the QGP.

1.4.1 Factorization Theorem

The cross-section for jet production in proton-proton collisions can be factorized at leading order into several independent probability distributions describing each stage of the process [45, 46, 47]. The cross-section for inclusive jets differential in p_T , the component of the jet's momentum which is transverse to the beam line, and η , the pseudorapidity, can be written as [48],

$$\frac{d\sigma^{pp \rightarrow jet+X}}{dp_T d\eta} = \sum_{abc} f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes J_c \quad (1.2)$$

where partons a and b from the incoming nuclei undergo a hard scattering and produce a parton c which fragments into a jet. The incoming partons are characterized by the parton distribution functions, $f_{a/p}$ and $f_{b/p}$, the hard scattering cross-section is H_{ab}^c , and the fragmentation into jets is described by the jet function, J_c . The symbol $\otimes$ denotes an integration over the longitudinal momentum fractions of the involved partons. The jet function, $J_c(z, p_T^{jet} * R)$, depends on the momentum fraction z of the parton c, and the product of jet momentum and jet radius parameter, $p_T R$. The jet function is a relatively new construction that emphasizes the fact that jets must be reconstructed by an algorithm and changing the algorithm's parameters may lead to different, equally correct results. The hard scattering cross-section is identical to the one in inclusive single hadron production at high p_T ,

$$\frac{d\sigma^{pp \rightarrow h+X}}{dp_T d\eta} = \sum_{abc} f_{a/p} \otimes f_{b/p} \otimes H_{ab}^c \otimes D_c^h \quad (1.3)$$

where D_c^h is the vacuum fragmentation function for parton c to fragment into a hadron h.

In heavy-ion collisions, the cross-section for jet production requires modifications to the PDFs and the jet function [48]. Nuclear PDFs are different from those in proton-proton collisions, but their impact on jet production is generally small. The jet function is modified by multiple scattering and energy loss to the medium, which are influenced by perturbative and nonperturbative effects. Modifications to the jet function are expressed to first order through a parametrized weight function,

$$J_c^{vac.}(z, p_T R) \rightarrow J_c^{med.}(z, p_T R) = W_c(z) \otimes J_c^{vac.}(z, p_T R). \quad (1.4)$$

Higher order corrections to the jet function are not well understood and arise from multiple scattering in the medium. The weight function, $W_c(z)$, is a function of

the momentum fraction z of the parton c and can only describe modifications due to energy loss.

1.4.2 Jet Reconstruction

Jet-finding algorithms are designed to cluster hadrons into jets based on their final state kinematic properties. The Snowmass accord [49] established the desiderata for jet-finding algorithms that led to the development of modern jet-finders. In summary, jet-finding algorithms should be easy to implement experimentally and theoretically, and the same algorithm should be used in theory and experiment for the results to be comparable. This entails a robust definition from final state hadrons and at any order of perturbation theory. The latter requirement suggests two properties of jet-finding algorithms, infrared safety and collinear safety. At higher orders in perturbation theory, the presence of soft radiation and collinear splitting of partons become more likely. Infrared safety requires that the presence of soft radiation should not change the jet reconstruction, and collinear safety requires that the presence of collinear splitting of partons should not change the jet reconstruction.

There are a number of different algorithms for reconstructing jets, including the anti- k_T algorithm [50], the k_T algorithm [51], and the Cambridge-Aachen algorithm [52], which all fall into the class of sequential recombination algorithms introduced for hadron collisions in [53]. These, together with SIScone [54] constitute all the infrared and collinear safe jet-finding algorithms. These jet-finding algorithms rely on a jet radius parameter, R , which determines the upper limit to the angular separation between particles in a jet and is chosen based on the analysis requirements.

Sequential Recombination Algorithms

Sequential recombination algorithms begin by defining a list of entities, either particles, tracks, detector hits, or groups of these, referred to as pseudojets. The algorithms proceed by sequentially and recursively grouping entities until every entity

is assigned to a jet. These algorithms define a distance measure between two entities, d_{ij} , and between an entity and the beam, d_{iB} . The distance measure between two entities is defined as

$$d_{ij} = \min(p_{Ti}^{-p}, p_{Tj}^{-p}) \frac{\Delta_{ij}^2}{R^2} \quad (1.5)$$

where p_{Ti} and p_{Tj} are the transverse momenta of entities i and j , respectively, $\Delta_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$, and R is the radius parameter. The distance measure between an entity and the beam is defined as

$$d_{iB} = p_{Ti}^{-p} \quad (1.6)$$

The algorithms find the minimum of d_{ij}, d_{iB} for each entity i . If the minimum is d_{ij} , then entities i , and j are combined into a pseudojet with a four-momentum given by the sum of the four-momenta of entities i and j . If the minimum is d_{iB} , then entity i is labeled as a jet and removed from the list of entities, repeating until there are no entities remaining. The anti- k_T algorithm uses $p=-2$, the k_T algorithm uses $p=2$, and the Cambridge-Aachen algorithm uses $p=0$. The anti- k_T algorithm tends to cluster higher momentum particles first, and reconstructs roughly conical jets. The k_T algorithm tends to cluster lower momentum particles first, and the Cambridge-Aachen algorithm clusters particles based on their angular separation.

1.4.3 Jet Background

We often assume a two-source model when reconstructing jets where jet constituents arise from either a hard-scattering or from a background. In proton-proton collisions, a small underlying event is produced, in addition to pile-up from the high rate of collisions at the LHC. In heavy-ion collisions, the presence of a QGP results in a large, fluctuating, and flow-correlated background. Since all final state hadrons are grouped

into jets, two types of backgrounds are expected: background-in-jet contamination, and combinatorial jets.

Background-in-jet contamination arises when background particles are swept into the jet, resulting in a different jet energy and axis compared with the true jet. Studies of pile-up in proton-proton collisions led to the development of techniques to mitigate the effects of background-in-jet contamination [50]. Use of these techniques is also feasible in heavy-ion collisions on average [55], though the large fluctuations in the background within an event limit the precision with which one can know the true jet energy on a jet-by-jet basis.

By assuming that the background contribution is proportional to the jet's area, the true jet energy can be estimated taking into account event-by-event fluctuations. The jet area is estimated by filling an event with many fake, very soft particles called ghosts and clustering them into jets. Because of infrared safety, this will not change the jets that are reconstructed. The jet area is proportional to the number of ghosts that are clustered into that jet. To estimate the background energy density, jets are reconstructed using the k_T algorithm after removing the two most energetic jets. The remaining jets are used to calculate the median energy density. The true jet momentum is estimated by subtracting the background energy density times the jet area from the jet's measured momentum.

Combinatorial jets are reconstructed entirely from background particles, either from pile-up or the QGP. These jets are not associated with any hard scattering, and are a result of high-momentum fluctuations in the background. The properties of combinatorial jets can be very different than jets associated with a hard-scattering and their contribution must be removed. Reducing the combinatorial jet background has often taken the form of kinematic cuts on the area of the jet and the momentum of its constituents [56]. This kind of kinematic selection is highly effective at reducing the influence of combinatorial jets, but it changes the population of jets that are studied [57].

1.4.4 Jet Modification

Because hard scatterings occur early on in heavy-ion collisions, their products interact with the QGP throughout its evolution, affecting both the jet's energy and possibly its hadrochemistry. As the initiating parton traverses the medium, it will radiate gluons and collide with medium partons. These interactions may cause the parton to give energy up to the medium and will cause the parton shower to evolve differently compared to a vacuum shower [58].

The nuclear modification factor, R_{AA} , describes the modification of hadrons and jets by comparing heavy-ion collisions to proton-proton collisions scaled by the number of binary collisions. The nuclear modification factor is defined as,

$$R_{AA} = \frac{\frac{dN^{AA}}{dp_T d\eta}}{\langle N_{coll} \rangle \frac{dN^{pp}}{dp_T d\eta}} \quad (1.7)$$

where $\frac{dN^{AA}}{dp_T d\eta}$ is the yield of either hadrons or jets in heavy-ion collisions, N_{coll} is the number of binary collisions and $\frac{dN^{pp}}{dp_T d\eta}$ is the yield of either hadrons or jets in proton-proton collisions.

Figure 1.8 shows a measurement of the nuclear modification factor for jets in heavy-ion collisions at the LHC performed by the ATLAS collaboration demonstrating that jets in 0–10% central collisions lose more energy than jets in 30–40% central collisions. Other measurements of the nuclear modification factor for charged jets carried out by CMS [59] and ALICE [60, 61] are consistent with the ATLAS results. This centrality dependence is related to the path length of the jet through the QGP and has been studied by ALICE [62, 63]. Jets in more central collisions traverse a greater volume of QGP and lose more energy. The dependence on the jet radius parameter has also been studied recently by ALICE [63] comparing jets reconstructed with $R=0.2$, 0.4 , and 0.6 . Figure 1.9 shows that the nuclear modification factor for jets reconstructed with $R=0.4$ is consistent with that of jets reconstructed with $R=0.2$, and that jets reconstructed with $R=0.6$ show a greater suppression. High

momentum hadrons have been used as a proxy for jets, and measurements of their nuclear modification factor find similar results. ALICE has measured charged hadron R_{AA} [64, 65], also as a function of centrality [66]. ALICE has also measured identified hadron R_{AA} [67, 68] showing reduced suppression for protons relative to pions and kaons with a dependence on centrality [69]. This is shown in Figure 1.10 which shows that the suppression of pions and kaons increases with increasing centrality at all transverse momenta. The dependence is much weaker for protons at intermediate transverse momenta but becomes more pronounced at higher transverse momenta.

Cold nuclear matter effects refer to differences between proton-proton and proton nucleus or deuteron nucleus collisions. In these systems, a QGP is not expected to form, but the presence of a nucleus could influence the production of hadrons and jets. Studies of heavy flavor production both at forward rapidities [70] and using leptons from heavy flavor decays [71] indicate that heavy flavor is suppressed in proton-lead collisions. Studies have also shown that J/Ψ particles are suppressed at forward rapidities in cold nuclear matter [72]. Measurements of the cold nuclear matter modification factor for inclusive hadrons in deuteron gold collisions, R_{dAu} at $\sqrt{s_{NN}} = 200$ GeV [73, 74] and in proton lead collisions, R_{pPb} at $\sqrt{s_{NN}} = 5.02$ TeV [75, 76, 77, 78] are consistent with one within systematic uncertainties and indicate that hadron suppression in heavy-ion collisions is not due to cold nuclear matter effects. Measurements of the cold nuclear matter modification factor for jets in proton-lead collisions at the LHC by the ALICE Collaboration [79] and the CMS Collaboration [80] show that jets are not suppressed in cold nuclear matter.

Measuring the ratio of strange to non-strange mesons and the ratio of baryons to mesons for jet constituents can shed light onto the processes that contribute to medium modification to the jet's hadrochemistry. Measurements of the proton to pion ratio for jet constituents in gold gold collisions with the STAR experiment at $\sqrt{s}=200$ GeV, Figure 1.11, show little modification relative to jets in proton-proton collisions within uncertainties [10]. Measurements of the Λ to K_s^0 ratio for jet constituents in lead-lead collisions from ALICE at $\sqrt{s}=2.76$ TeV, Figure 1.12 show

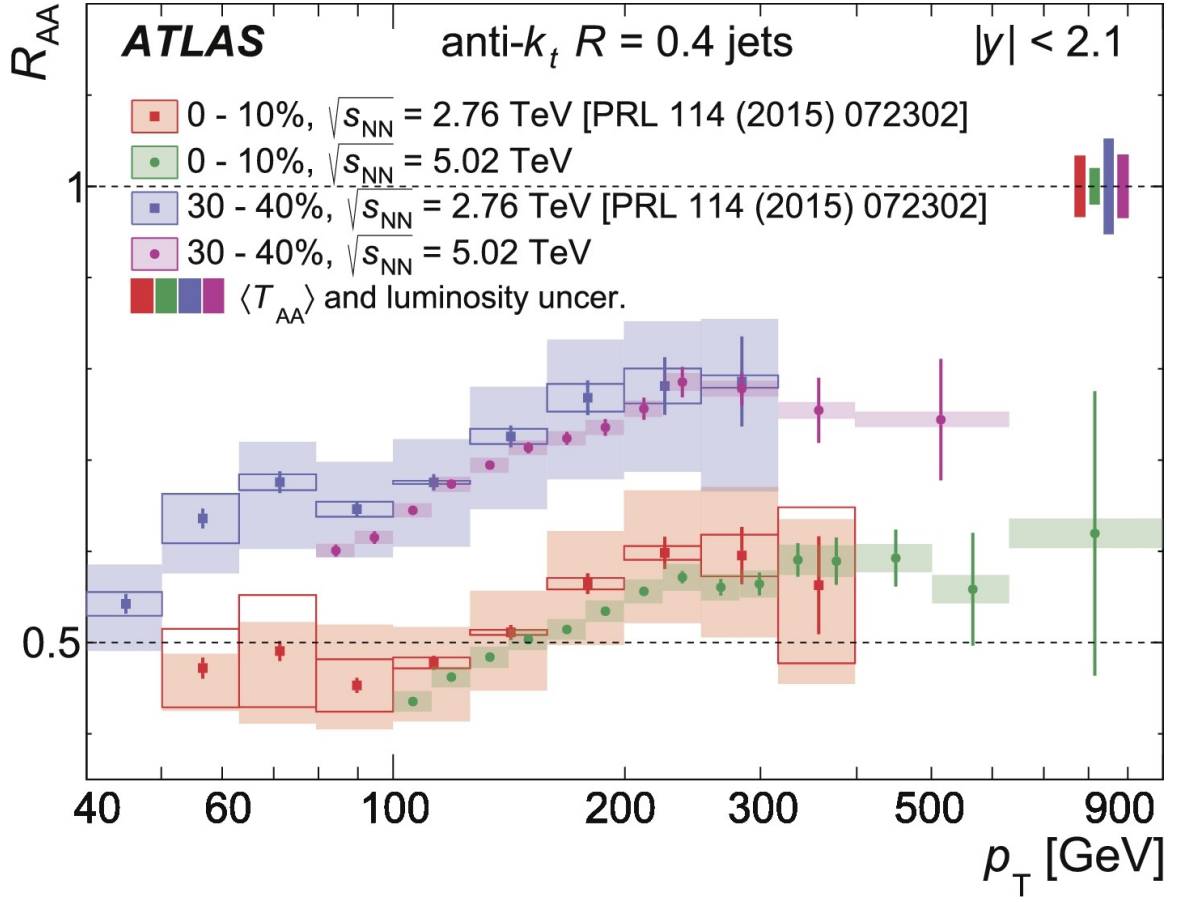


Figure 1.8: The nuclear modification factor for jets in heavy-ion collisions at the LHC measured by the ATLAS collaboration. [7]

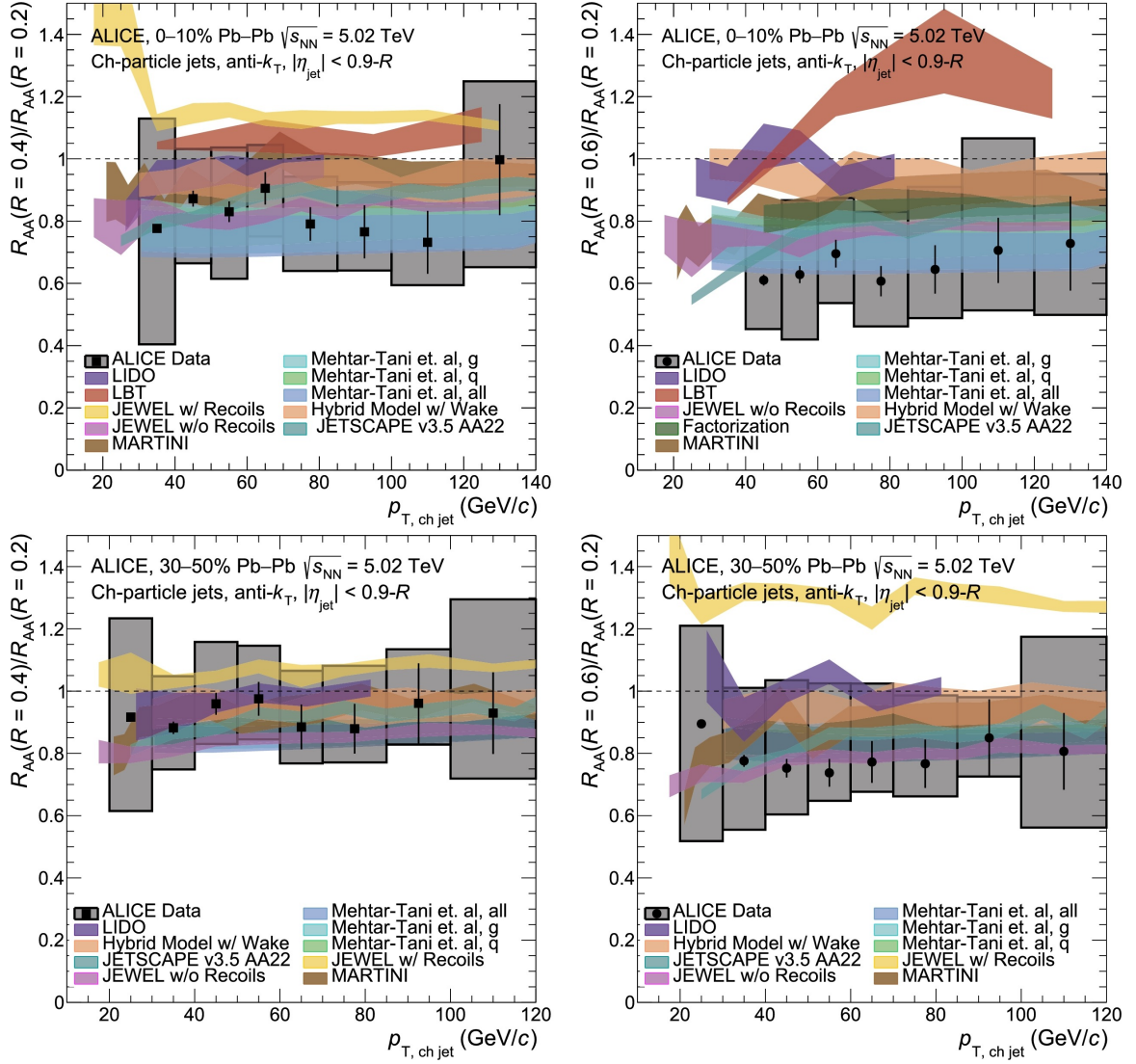


Figure 1.9: The nuclear modification factor for jets in heavy-ion collisions at the LHC measured by the ALICE collaboration as a function of the jet radius parameter. [63]

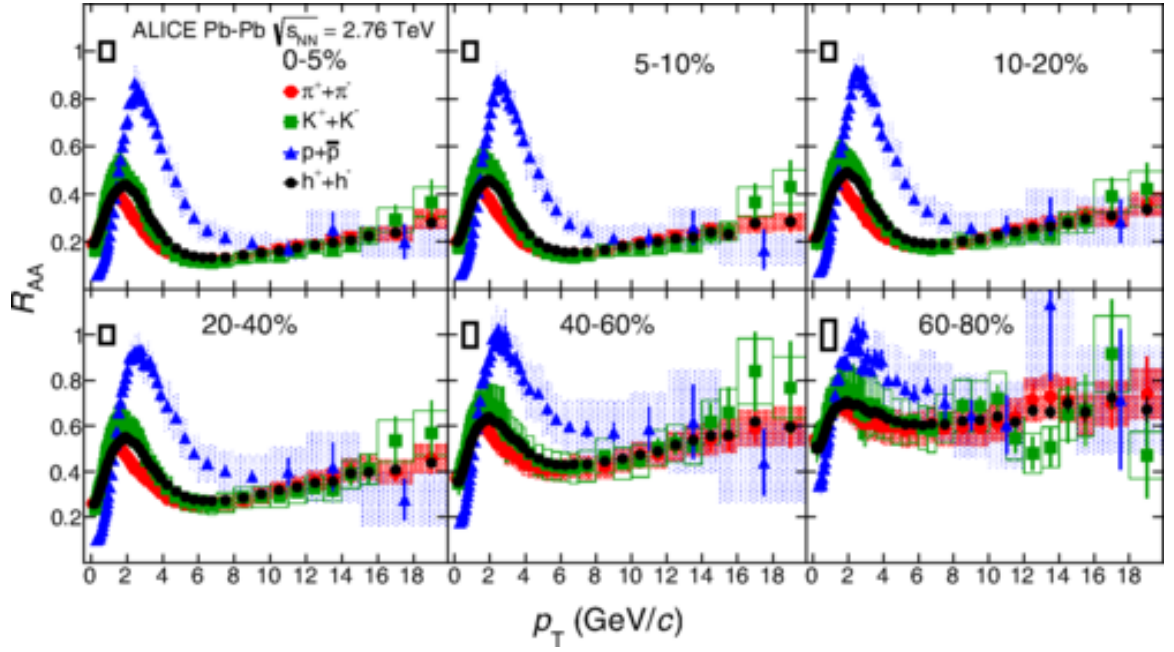


Figure 1.10: The nuclear modification factor for identified hadrons as a function of centrality in heavy-ion collisions at the LHC measured by the ALICE collaboration. [69]

little modification except at the lowest momentum bins where a clear definition of the jet is impossible [11]. Within uncertainties, there is no modification of the baryon to meson ratio for jets in heavy-ion collisions.

Studies of dihadron correlations provide a complementary view of the modifications to jet hadrochemistry. Dihadron correlations measure the properties of hadrons relative to a high- p_T trigger. Of particular interest are the hadrons that are in the vicinity of a high- p_T hadron, and those that are 180° away in azimuth. Figure 1.13 shows measurements of the proton to pion and Λ to K_s^0 for hadrons in the vicinity of a jet (near-side) and those opposite in azimuth (away-side) from the STAR experiment [12]. While the near-side hadrons show little modification relative to proton-proton collisions, the away-side hadrons show a hint of modification. Another measurement of the Λ to K_s^0 in Cu-Cu collisions by STAR shows a similar lack of enhancement on the near side, as seen in Figure 1.14. It is important to note that the flow-correlated background was not properly corrected for in these analyses, only taking v_2 into account. Measurements of the proton-to-pion ratio for hadrons from jet-hadron correlations in gold gold collisions at $\sqrt{s}=200$ GeV by the STAR experiment [14, 15] show similar behavior to the baryon-to-meson ratios from dihadron correlations, shown in Figure 1.15. Since this study has been undertaken, the field has developed its understanding of the background, though the qualitative results hold up. These measurements may indicate that away-side jets are more modified than near-side jets, possibly traversing a larger volume of the QGP, although the effect is small.

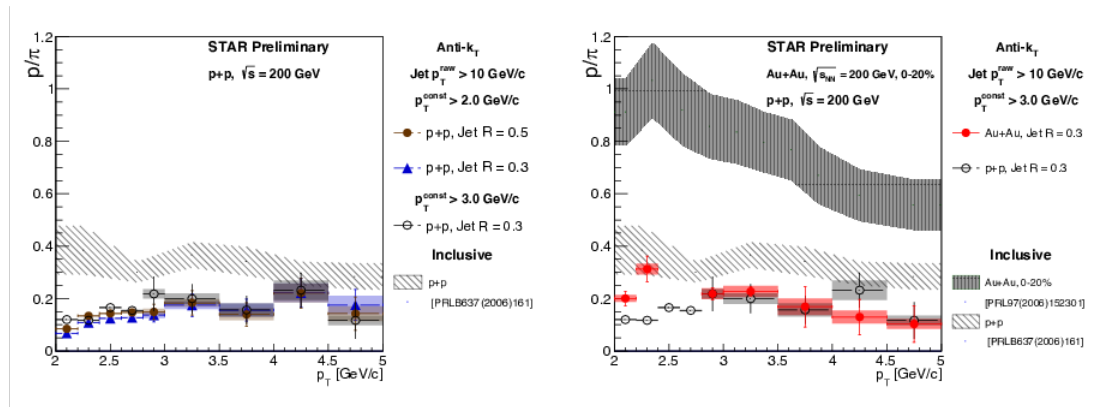
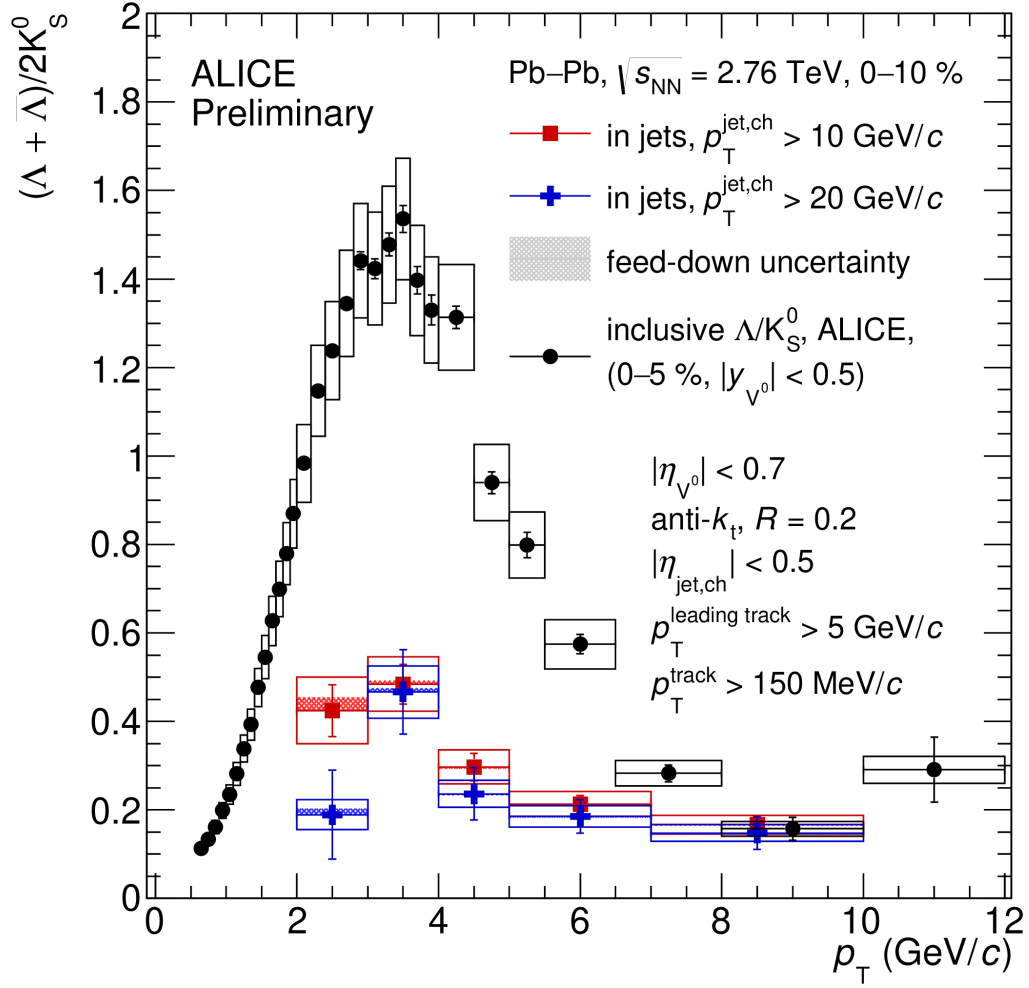


Figure 1.11: The proton to pion ratio for jet constituents in gold gold collisions relative to proton-proton collisions measured by the STAR experiment at $\sqrt{s}=200$ GeV. [10]



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Figure 1.12: The Λ to K_s^0 ratio for jet constituents in lead-lead collisions relative to proton-proton collisions measured by the ALICE experiment at $\sqrt{s}=2.76$ TeV. [11]

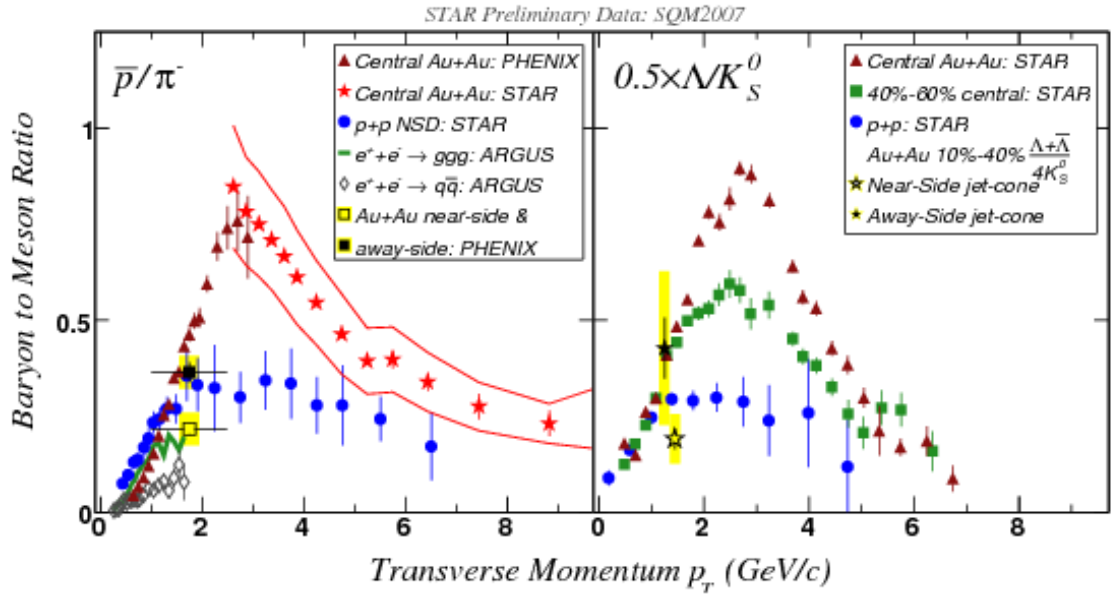


Figure 1.13: The proton to pion and Λ to K_s^0 ratios for hadrons in the vicinity of a jet and those 180° away in azimuth measured by the STAR experiment at $\sqrt{s}=200$ GeV [12]

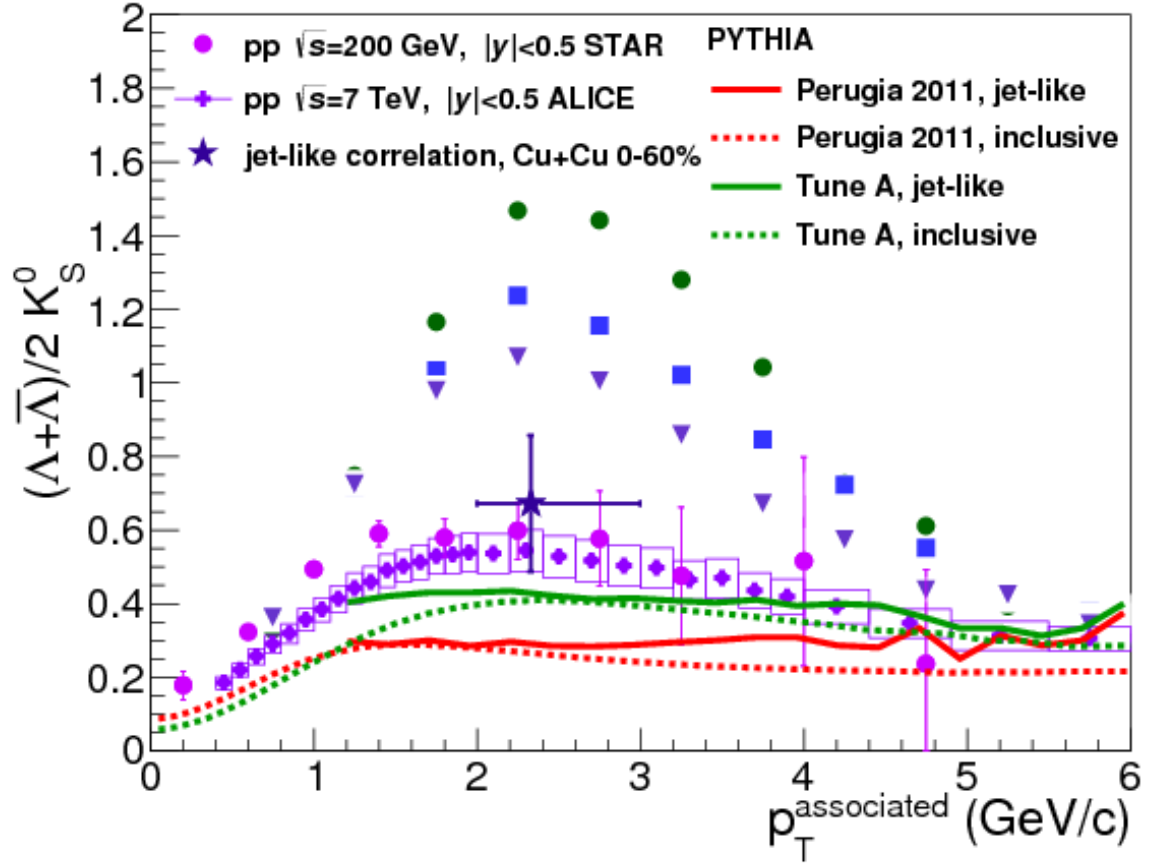


Figure 1.14: The Λ to K_s^0 ratio for hadrons in the vicinity of a jet measured by the STAR experiment in Cu-Cu collisions at $\sqrt{s}=200$ GeV [13]

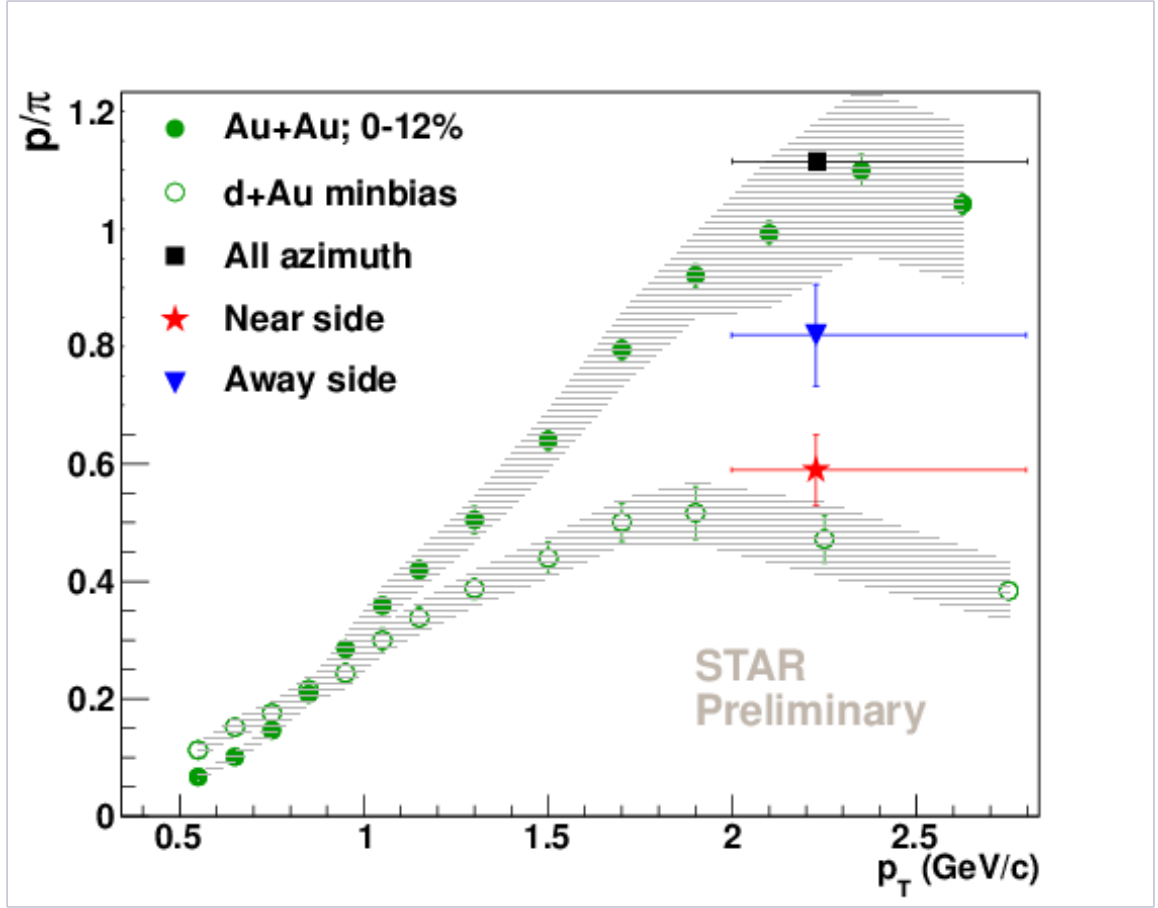


Figure 1.15: The proton to pion ratio for hadrons in the vicinity of a jet and those 180° away in azimuth measured by the STAR experiment at $\sqrt{s}=200$ GeV [14]

Chapter 2

A Large Ion Collider Experiment at the Large Hadron Collider

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is a 27 km synchrotron accelerator located at CERN in Geneva, Switzerland and extending into France roughly 100 meters underground. While it was originally designed to collide protons at energies of $\sqrt{s}=14$ TeV, the LHC only reached a max energy of 8 TeV in Run 1. Lead ions were designed to be collided at $\sqrt{s_{NN}}=2.76$ TeV per nucleon pair in Run 1. In Run 2, the LHC collided proton beams at energies of $\sqrt{s}=13$ TeV and lead ions at $\sqrt{s_{NN}}=5.02$ TeV per nucleon pair. There was an additional period during which the proton beams were collided at $\sqrt{s}=5.02$ TeV for direct comparisons at the lead ion collision energy. The LHC was primarily built to discover the Higgs Boson and search for evidence of supersymmetry, but many other measurements are possible at the LHC.

The LHC was constructed from 1998 to 2008 and began operation in 2009. There are four major experiments situated along the ring at various interaction points: A Large Ion Collider Experiment (ALICE), A Toroidal LHC Apparatus (ATLAS), Compact Muon Solenoid (CMS), and Large Hadron Collider beauty(LHCb). A schematic

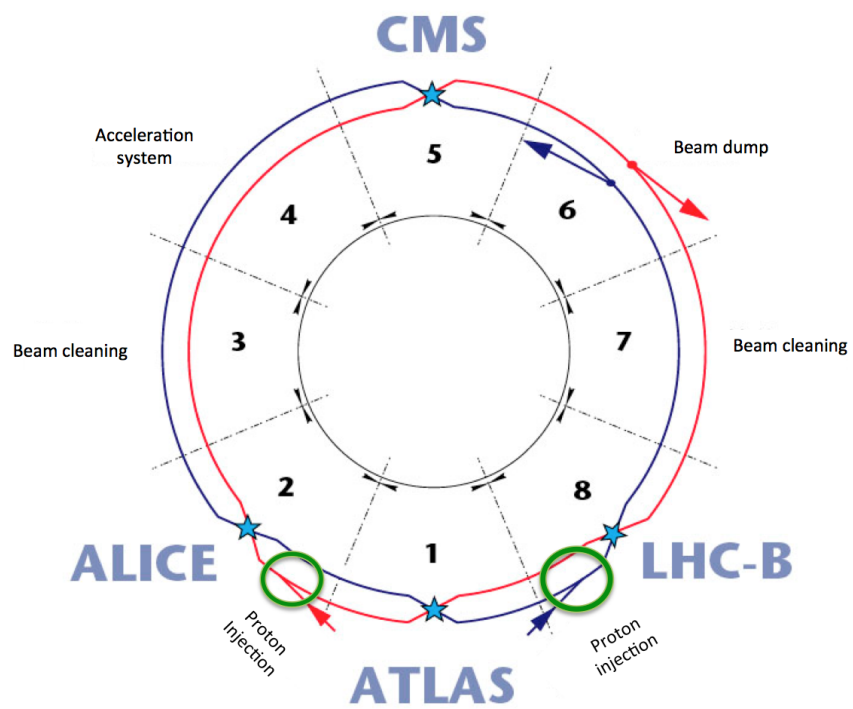


Figure 2.1: Schematic of the LHC showing the four major experiments

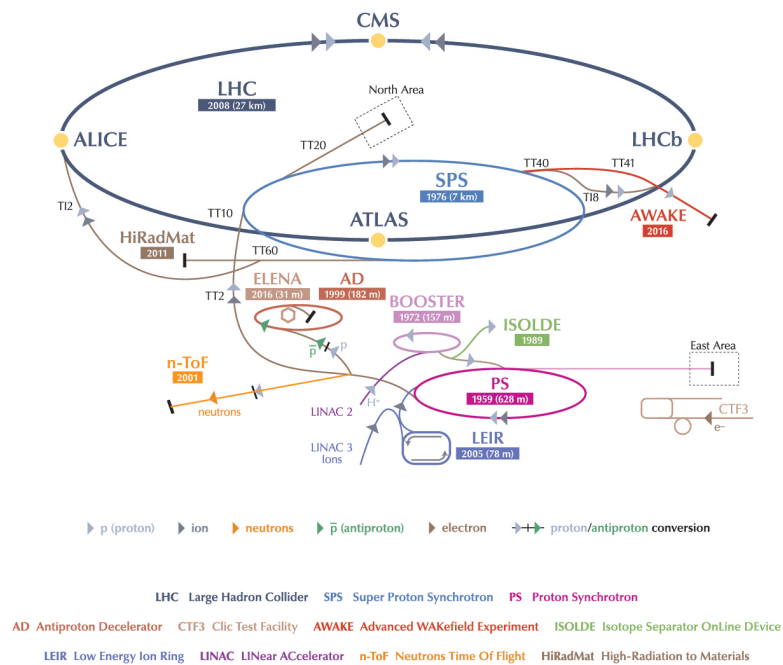


Figure 2.2: CERN Accelerator Complex showing the journey that protons take to arrive in the LHC [81]

complicated task that requires monitoring and adaptive action. These measurements would not be possible without the diligent efforts of the LHC operations staff.

2.2 A Large Ion Collider Experiment

The ALICE detector, shown in Figure 2.3, is specifically designed to analyze the products of heavy-ion collisions in the LHC. The total volume of the detector is $16 \times 16 \times 26 \text{ m}^3$. The total weight of the ALICE detector is approximately 9000 metric tons. Surrounding the central barrel is the L3 solenoid magnet which bends charged particle tracks for momentum measurements using a field of 0.50 T. The ALICE detector is composed of several sub-detectors which provide specific functionality. The main tasks of the ALICE detector are triggering, tracking, particle identification, and calorimetry. Triggering signals when an interesting event is occurring so that it can be written out to disk. Tracking provides position and momentum information through a large volume of the detector. Particle identification(PID) leverages many sub-detectors to identify particle species. Calorimetry provides a direct measurement of the energy. Triggering uses information processed in the Central Trigger Processor from several sub-detectors to make the decision to write the event to disk or not. The sub-detectors which provide triggers include the V0, T0, and the EMCal. Tracking encompasses the group of sub-detectors in the Central Barrel; these include the ITS and the TPC. Coupled with the L3 magnet, positional tracking in the central barrel and momentum information for charged particles can be measured. Several detectors in ALICE provide signals that are used for particle identification. The ITS and TPC provide energy loss vs. momentum measurements, and the TOF provides time-of-flight measurements. The TRD allows discrimination based on transition radiation behavior, and the HMPID extends the identification capabilities for p and K to higher momentum via ring-imaging Cherenkov detectors. Calorimetry is composed of three electromagnetic calorimeters: the EMCal, DCal, and the PHOS. The EMCal and DCal are situated roughly 180° in ϕ from each other allowing for

THE ALICE DETECTOR

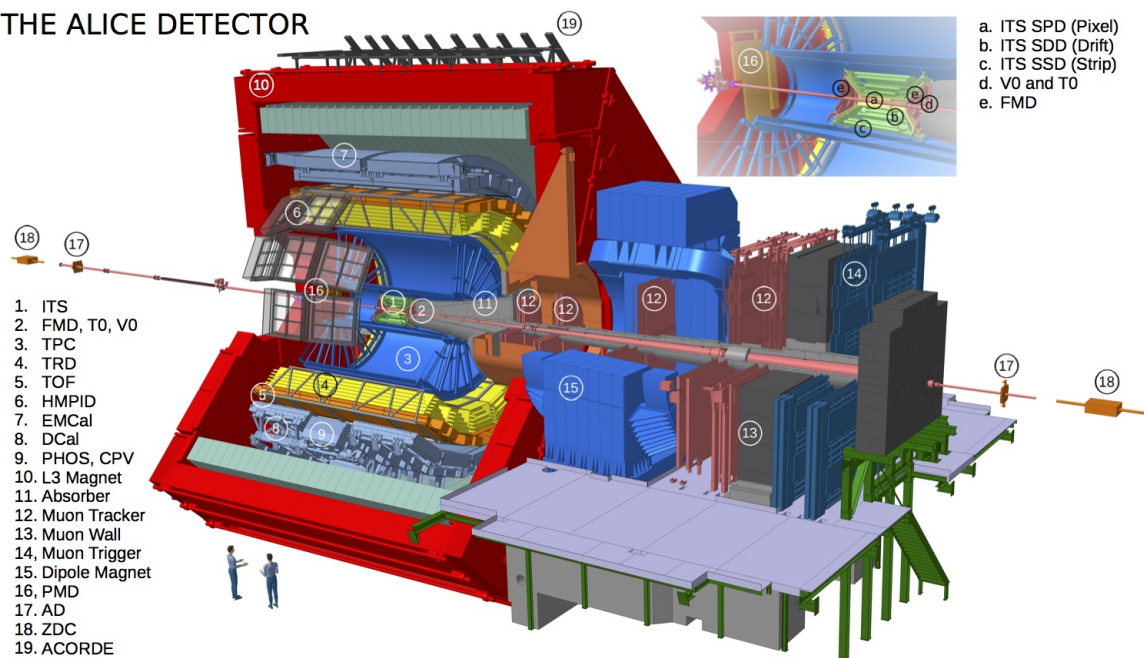


Figure 2.3: Schematic of the ALICE detector

dijet measurements, and the PHOS is a high resolution calorimeter used primarily for photon measurements. The following sections will describe the sub-detectors which are used in this analysis in more detail.

2.2.1 V0 Detector

The V0 detector is a two-layered array of 32 scintillation counters. It is installed around the ALICE interaction point in two pieces, V0A and V0C, covering the backward and forward regions, respectively. The V0 detector's main functions are providing Minimum Bias and Centrality triggers, measuring the reaction plane resolution, and determining the centrality for p-p, p-A, and A-A collisions. The detector covers pseudorapidity ranges $2.8 \leq \eta \leq 5.1$ (V0A) and $-3.7 \leq \eta \leq -1.7$ (V0C) with full azimuthal coverage. The V0A array is located 330 cm in front of the IP along the beam line on the A side, the V0C array is located 90 cm after the IP along the beam line. Each array is segmented into counters separated into four ring structures, shown below in Figure 2.4. The Minimum Bias trigger, provided by the V0, requires signal in both arrays for an event to be recorded; this is referred to as AND mode. In addition, one can require more specific triggers: Multiplicity trigger, Semi-Central trigger, Central trigger, and a Minimum Bias p-Gas trigger. In realistic p-p collisions, for non-diffractive collisions, the V0 will detect at least one charged particle in both arrays with an efficiency of approximately 84% [82]. In this analysis, the Minimum Bias trigger is used to select events in p-p collisions, and both the Central and Semi-Central triggers are used to select events in Pb-Pb collisions.

The V0 detector provides a measurement of the charged particle multiplicity based on the energy deposited in the scintillators. A detailed simulation of the V0 apparatus was used to extract the relationship between charge collected inside a V0 ring and the charged particle multiplicity in the corresponding η range. The distribution of charged particle multiplicities, $\frac{dN_{ch}}{d\eta}$ is then obtained in η bins corresponding to the scintillator rings of the V0. Figure 2.5 shows an example of a distribution of V0 amplitudes.

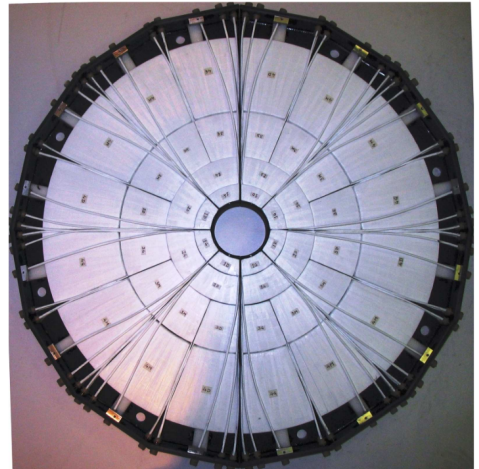
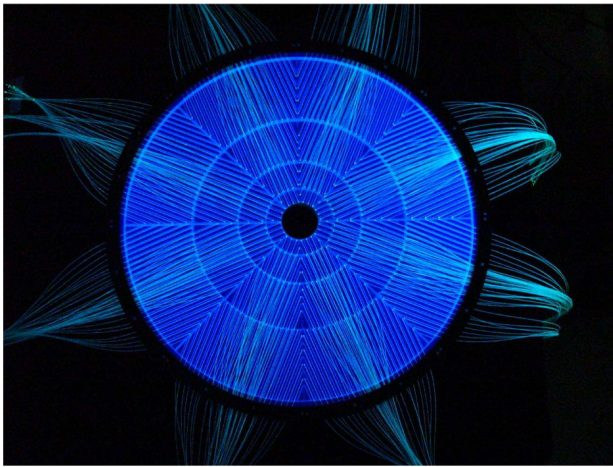


Figure 2.4: Schematic of the V0 detector

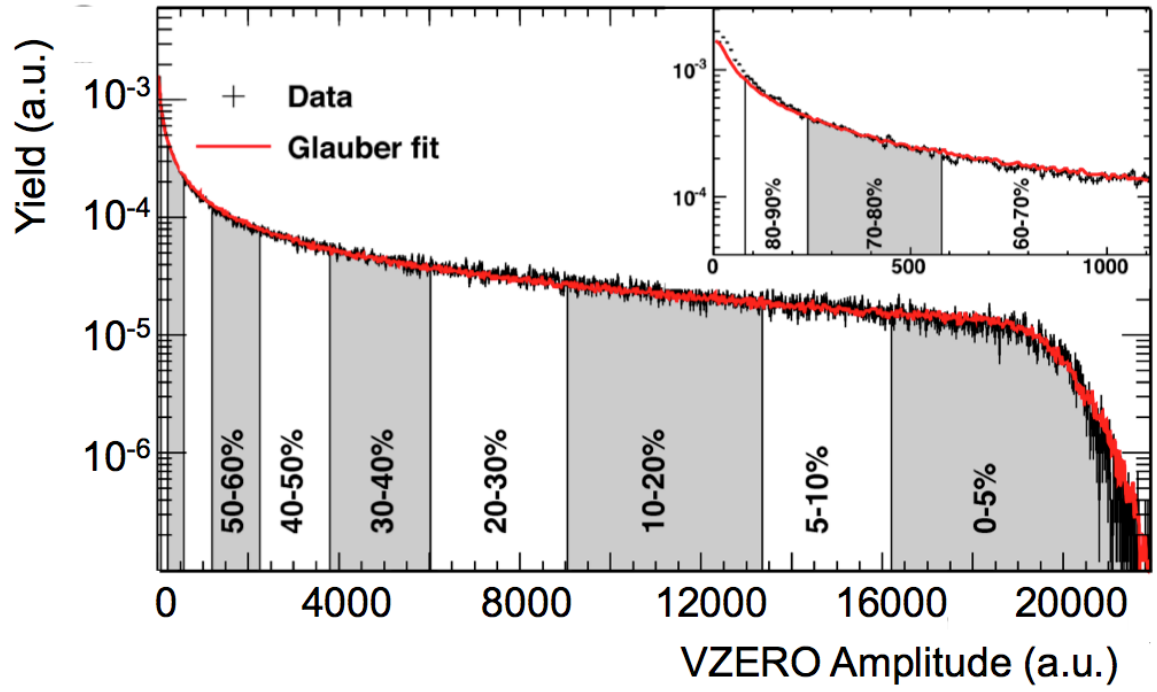


Figure 2.5: V0 amplitude distribution for a single ring

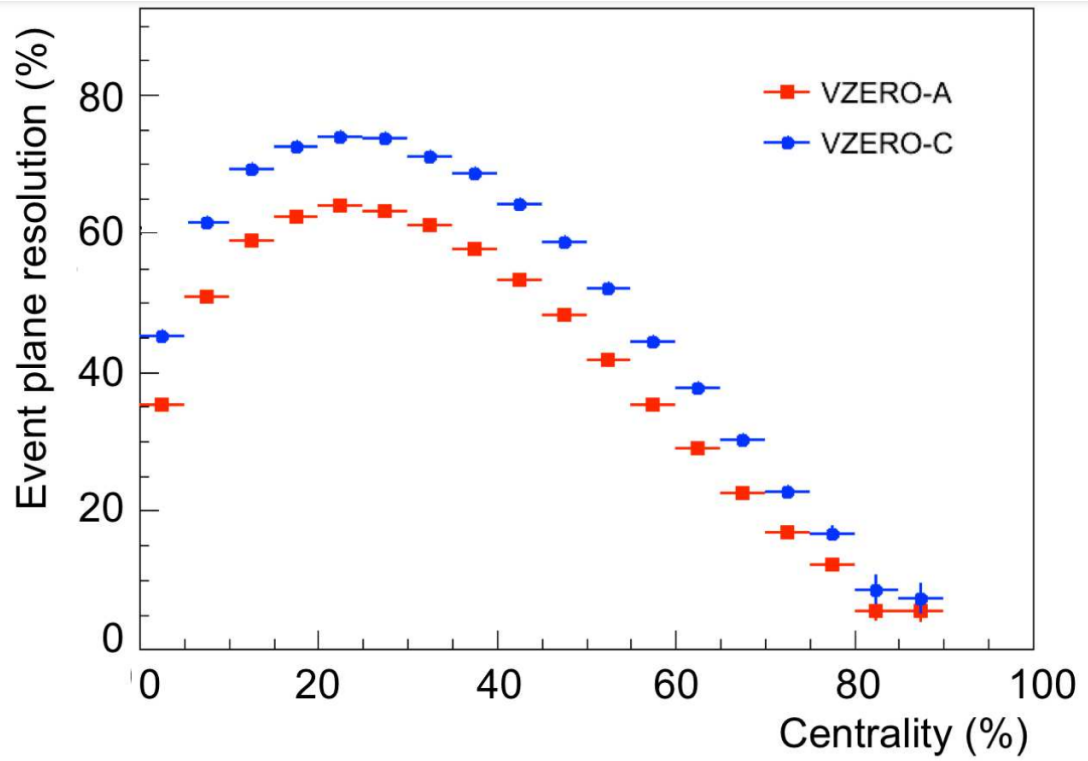


Figure 2.6: Reaction plane resolution as a function of charged particle multiplicity

This distribution is fit using a Monte Carlo Glauber model which reproduces the V0 amplitude distribution, and hence the centrality, for all but the most peripheral collisions. For low multiplicity events, the most peripheral collisions, the minimum bias trigger efficiency is not 100%. Therefore the most peripheral collisions require the Glauber fit to be extrapolated. The V0 detector additionally provides a measurement of the participant plane, Ψ_n , an experimental determination of the true reaction plane, Ψ_{RP} . The V0 detector is also used to determine the event plane resolution, the accuracy with which the event plane reproduces the true orientation of the reaction plane [83]. The reaction plane resolution depends on the multiplicity of charged particles in the collision, shown in Figure 2.6.

2.2.2 T0 Detector

The (T0) detector consists of two arrays of Cherenkov counters, T0C and T0A on either side of the interaction point. The T0 detector is used to provide a start time for the Time-of-Flight detector, described in 2.2.6. The T0 detector is also used to measure the vertex position. Each detector array is composed of 12 cylindrical counters coupled with photomultiplier tubes. The T0C and T0A arrays are located at approximately 70 cm and 370 cm away from the interaction point respectively. They both cover the full range of azimuth as well as $-3.28 \leq \eta \leq -2.97$ (T0C) and $4.61 \leq \eta \leq 4.92$ (T0A). Figure 2.7 shows the interaction time measured in the T0 with respect to the LHC clock, and Figure 2.8 the resolution measured as the difference between the T0A and T0C. The T0 detector is used in this analysis to provide a start time for the TOF detector.

2.2.3 Inner Tracking System

The Inner Tracking System (ITS) detector is composed of six concentric layers of cylindrical silicon detectors: two layers each of the Silicon Strip Detector (SSD), Silicon Drift Detector (SDD), and Silicon Pixel Detector (SPD). The ITS has the main

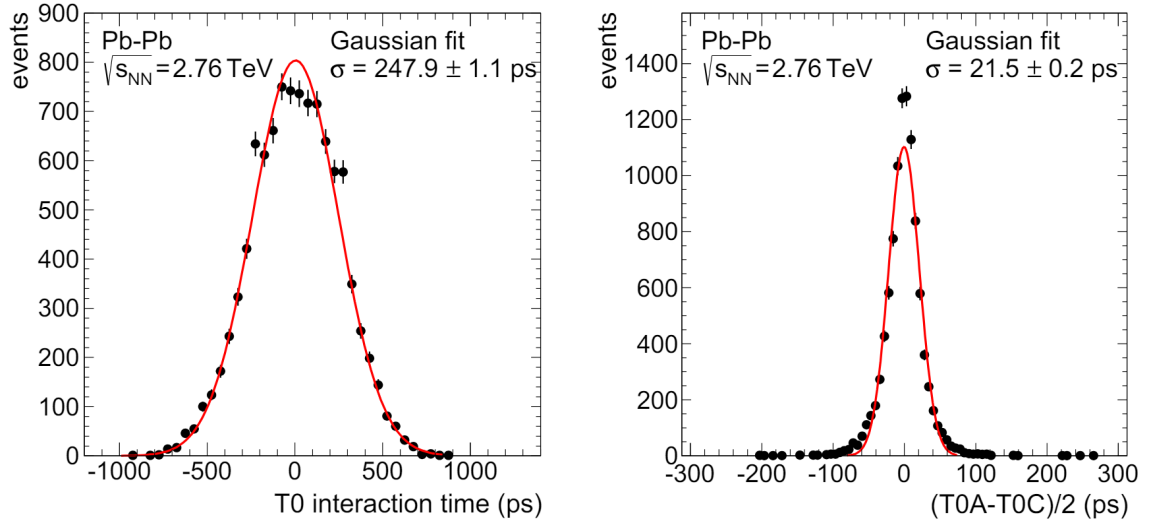
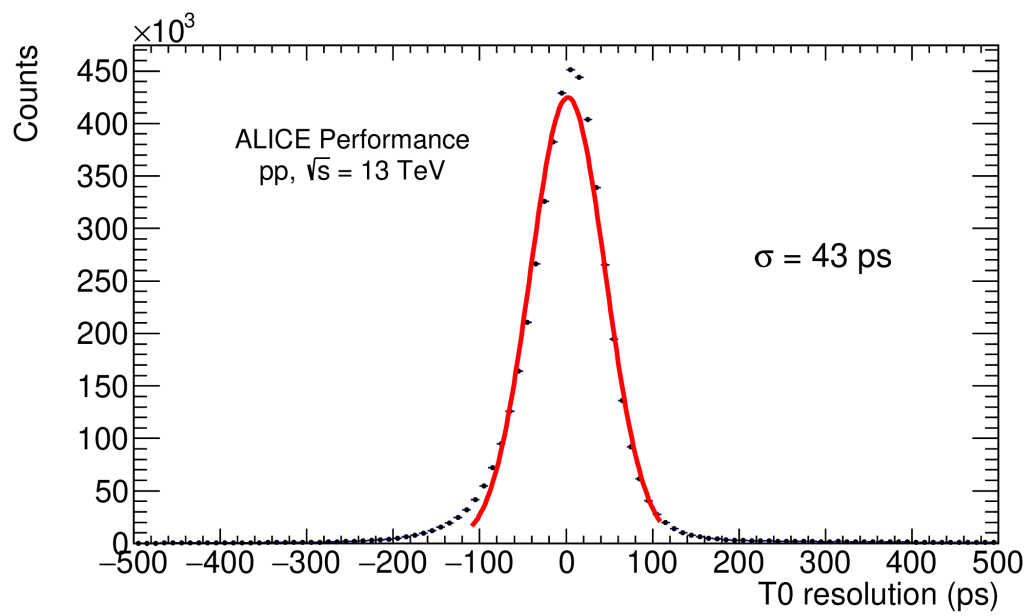


Figure 2.7: Interaction time measured in the T0 with respect to the LHC clock [84]



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Figure 2.8: Resolution of the T0 detector [84]

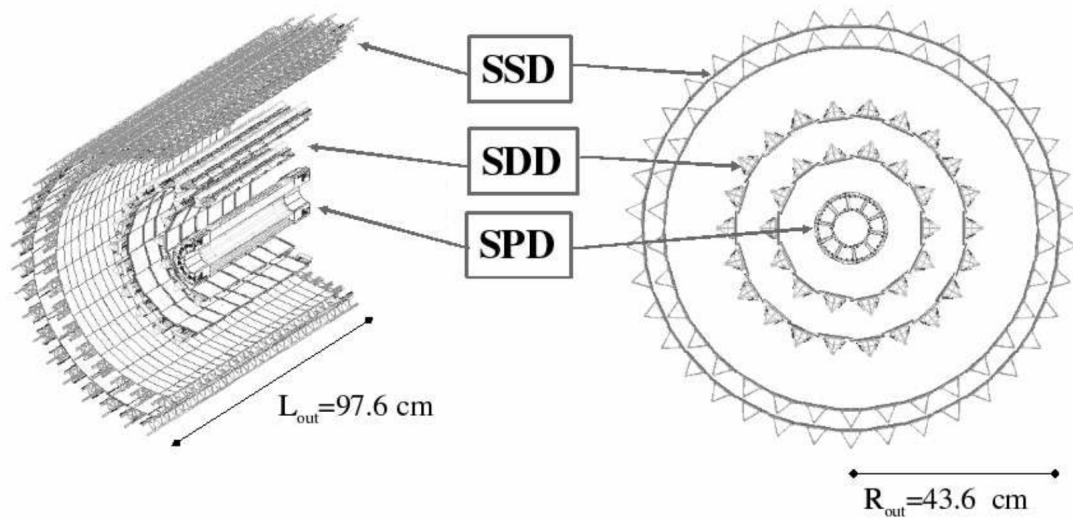


Figure 2.9: Schematic of the ITS detector [84]

functions of measuring primary and secondary vertices, as well as charged particle tracking and particle identification capabilities. The ITS surrounds the interaction point with a full azimuthal range, pseudorapidity $|\eta| \leq 0.9$, and a radial coverage of $3.9 \text{ cm} \leq r \leq 43.0 \text{ cm}$. The SDD and SSD both provide a read-out of the signal amplitude and thus contribute to PID in ALICE through $\frac{dE}{dx}$ measurements. Using a truncated mean of up to four signals a $\frac{dE}{dx}$ resolution of 12% [84] is measured. Figure 2.9 shows a schematic view of the ITS with the SPD, SDD, and SSD layers highlighted in stereographic (left) and transverse (right) projections. The ITS is not used for particle identification in this analysis. This is because the momentum range in which the ITS can effectively separate particle species is below 1 GeV/c, and this analysis does not consider these particles. However, the ITS is used for primary vertex determination and in track reconstruction.

2.2.4 Time Projection Chamber

The ALICE Time Projection Chamber is a 92 m^3 cylindrical barrel filled with a gas mixture of 10% CO₂ and 90% Ne. The barrel has a radial extent of $84.8 \text{ cm} \leq r \leq 246.6 \text{ cm}$, covering the full azimuth and $|\eta| \leq 0.9$. It is separated by its axial center into two drift regions which comprise the primary tracking volumes in ALICE. The TPC provides tracking for charged particles moving through its active volume. Charged particles traverse the drift regions and ionize gas along their path. The drift regions provide a constant drift field along the beam direction of 400 V/cm that directs the liberated electrons towards the anodes located at the end caps of the TPC. The electrons induce an avalanche effect on the wires near the anode providing the necessary signal amplification for readout. The TPC contains 557568 readout channels and has a resolution of 800 to 1100 μm in the R and ϕ directions, and 1100 to 1250 μm in the direction of the beam axis.

Particle identification can be done in the TPC for pions, protons, kaons and electrons by measuring the specific energy loss, $\frac{dE}{dx}$, due to ionization as these particles

traverse the gaseous volume. The $\frac{dE}{dx}$ measurements for the TPC are shown for p-p collisions at 7 TeV in Figure 2.10. The specific energy loss is calculated using the Bethe-Bloch formula, however, experimentally other parametrizations are used which simplify calculations for specific gas mixtures. The solid lines in Figure 2.10 are given by the ALEPH parameterization of the Bethe-Bloch formula given in Eq 2.1. The parameters are fixed by the gas mixture. The TPC has an average $\frac{dE}{dx}$ resolution of $\sigma(\frac{dE}{dx})/\langle\frac{dE}{dx}\rangle = 7\%$, but in general the resolution scales inversely with the square root of the number of TPC track points for the track in question, $\sigma(\frac{dE}{dx}) \propto 1/\sqrt{n}$.

$$f(\beta\gamma) = \frac{P_1}{\beta^{P_4}} \left(P_2 - \beta^{P_4} - \ln \left(P_3 + \frac{1}{(\beta\gamma)^{P_5}} \right) \right) \quad (2.1)$$

The TPC can be used to identify particle species on a track-by-track basis at low momentum, and statistically at higher momentum. In this analysis we propose a new statistical technique described in 3.3 that can be applied across the entire momentum range.

2.2.5 Electromagnetic Calorimeter

The ALICE Electromagnetic Calorimeter and Dijet Calorimeter are lead-tungsten scintillating detectors designed to measure all electromagnetically interacting particles, including electrons from heavy-flavor hadron decays, the electromagnetic component of jets, and spectra of direct photons and photons from neutral meson decays. The calorimeters enable triggering and full reconstruction for jets within their acceptances. The EMCAL covers a range of 107° in ϕ and $|\eta| \leq 0.7$, and the DCAL encompasses two azimuthal ranges with different pseudorapidity ranges: $260 < \phi < 320$ with $0.22 < |\eta| < 0.7$ and $320 < \phi < 327$ with $|\eta| < 0.7$. The EMCAL is segmented into 12288 6.0 cm x 6.0 cm x 24.6 cm optically isolated rectangular prisms (towers) of 76 alternating layers of the scintillator (Polystyrene) and absorber (PbWO₄). The towers are grouped into units called supermodules. The DCAL is constructed from the same technology used in the EMCAL. Figure 2.11 shows a

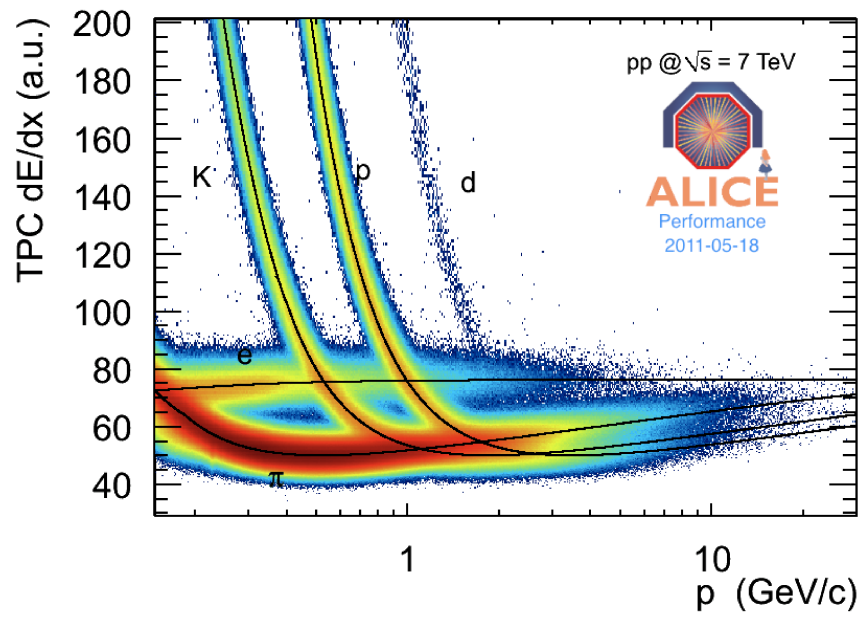


Figure 2.10: Specific energy loss in the TPC for p-p collisions at 7 TeV

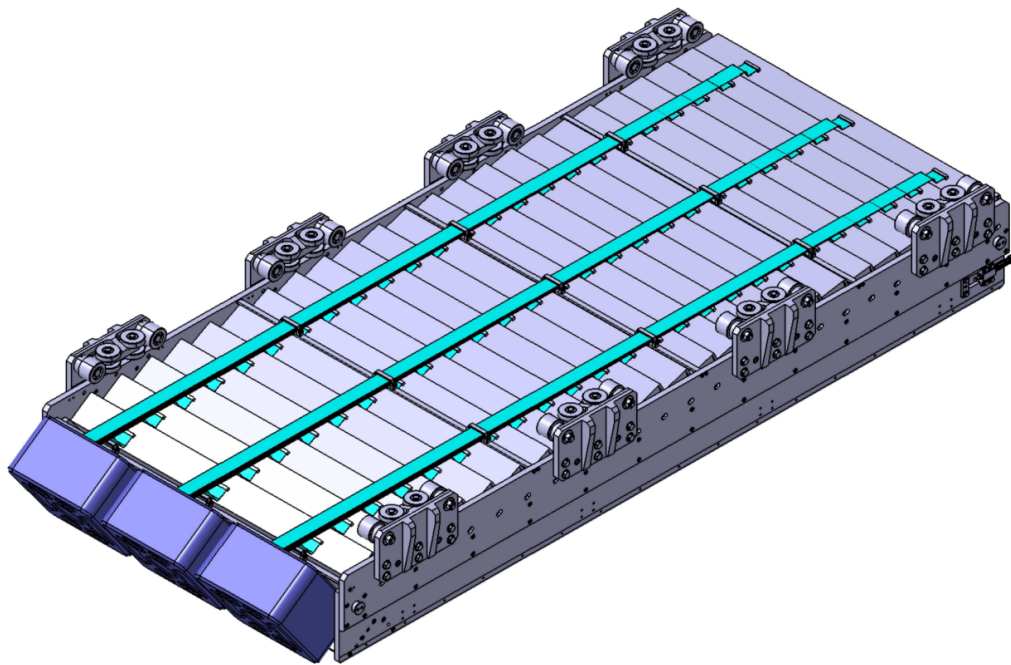


Figure 2.11: Drawing of an EMCal supermodule

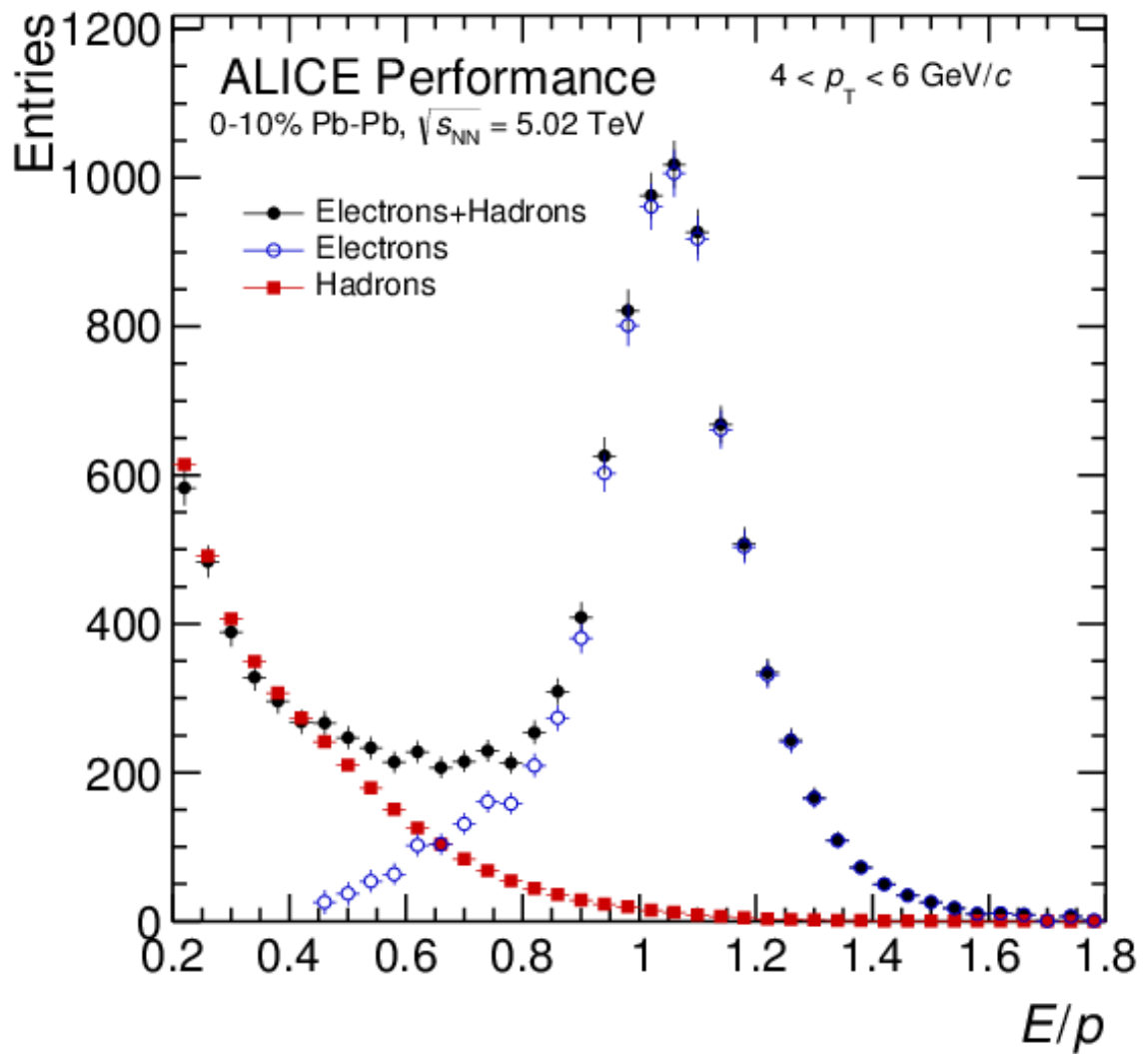
drawing of one of the super modules. When a particle is incident on the calorimeter, the particle's energy is deposited in the detector, producing light via scintillation. Scintillation is the process where a material will re-emit energy absorbed as light when struck with ionizing radiation. The light then travels through fiber optic cables terminating at avalanche photo- diodes. The resulting amplified signal is fed into a charge sensitive pre-amplifier and digitized using the Front End Electronics cards.

The EMCal can be used for a high-purity identification of electrons due to the fact that they deposit almost all of their energy in the EMCal. Figure 2.12 shows the ratio of the energy measured in the EMCal detector to the momentum measured in the TPC for a given particle. Electrons and photons deposit most of their energy in the EMCal, but the photons leave no signal in the TPC, resulting in a peak near one for electrons. Hadrons typically do not deposit all of their energy within the radial length of the EMCal. The calorimeters are used in order to trigger on jet events as well as to study the neutral component of jets. They are designed with triggering electronics for a fast, efficient high- p_T jet trigger. With an enhanced sample of events containing high- p_T jets, they can be studied with lower uncertainty. Furthermore, measuring the neutral component of jets allows us to study the full energy content of jets. This allows us to compare jet measurements to perturbative calculations directly. In this analysis, the jet trigger is not used to avoid any potential bias in the jet spectrum. The calorimeters are used to measure a portion of the neutral component in jets.

2.2.6 Time-of-Flight Detector

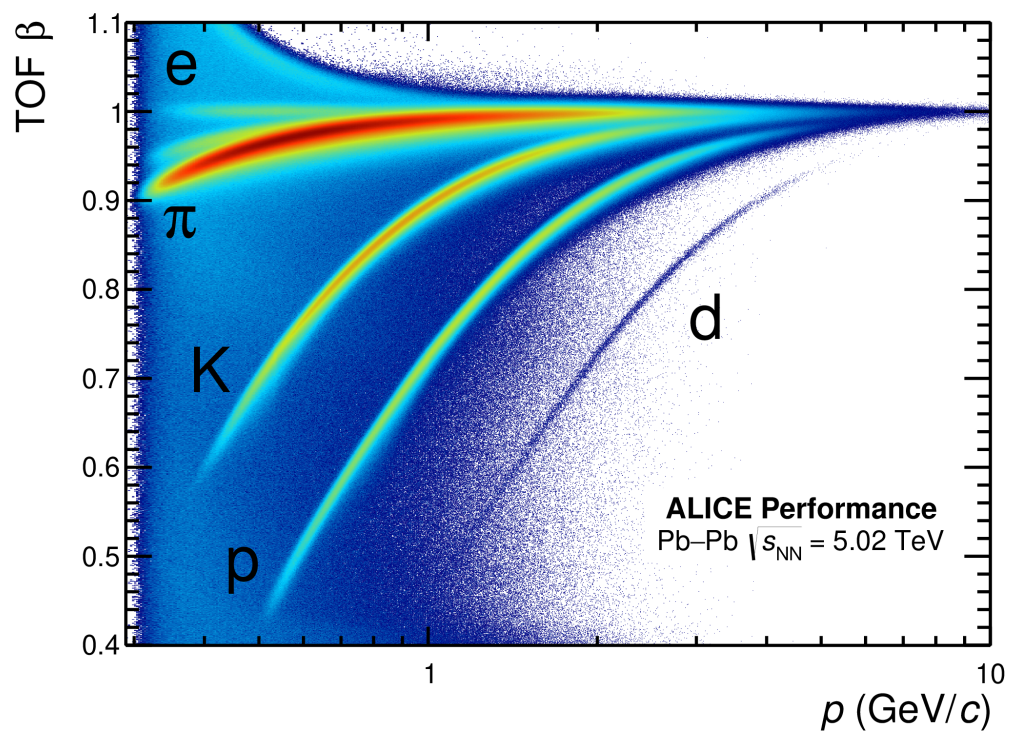
The ALICE Time-of-Flight (TOF) Detector is a large area array of Multi-gap Resistive Plate Chambers (MRPCs) designed to provide particle identification for charged particles in the intermediate momentum range. Additionally, the TOF serves as a trigger for cosmic and ultra-peripheral events. The TOF covers a range of $|\eta| \leq 0.9$ and 2π in ϕ . The TOF is composed of 1593 MRPC strips arranged in 18 azimuthal sectors. On average, the TOF provides a time resolution of 80 ps.

The TOF provides PID for charged particles by comparing the measured time-of-flight of each track with the expected time-of-flight for a given particle species at a given momentum. Figure 2.13 shows the particle velocity ($\beta = v/c$) as a function of momentum. The pion, kaon, and proton bands are labeled along with electrons and deuterium. The TOF provides clean separation between pions and kaons up to momentums of roughly 3 GeV/c and clean separation between protons and kaons up to momentums of roughly 5 GeV/c. The TOF is used in this analysis to calibrate the distributions of pions, kaons and protons for further analysis. This is described in 3.3.3.



ALI-PERF-119871

Figure 2.12: Ratio of the energy measured in the EMCal to the momentum measured in the TPC



ALI-PERF-106336

Figure 2.13: Particle velocity as a function of momentum

Chapter 3

Methods

3.1 Data

We used data from proton-proton collisions at $\sqrt{s} = 5.02$ TeV and Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV which were collected during Run 2 of the LHC by the ALICE detector using a minimum bias trigger. This analysis studies 0-10% centrality Pb-Pb collisions, referred to as central, and 30-50% centrality Pb-Pb collisions, referred to as semicentral. See Table 3.1 for details about the number of events, jets, and associated hadrons used in this analysis.

3.1.1 Event Selection

We apply the following event selection criteria which are similar to [85, 86] and are standard for ALICE jet analyses. We require the primary vertex in all events to have at least one track contributing to its determination. We also require that this globally-determined vertex is within 0.2 mm of the vertex determined by the SPD alone. The primary vertex must lie within 10σ in spatial resolution of the SPD and 20σ in spatial resolution of the global vertex, and the spatial resolution of the SPD vertex determination must be less than 2.5 mm. We also require that the primary vertex is within 10 cm of the nominal interaction point along the beam axis. We

Table 3.1: Event statistics for the data used in this analysis.

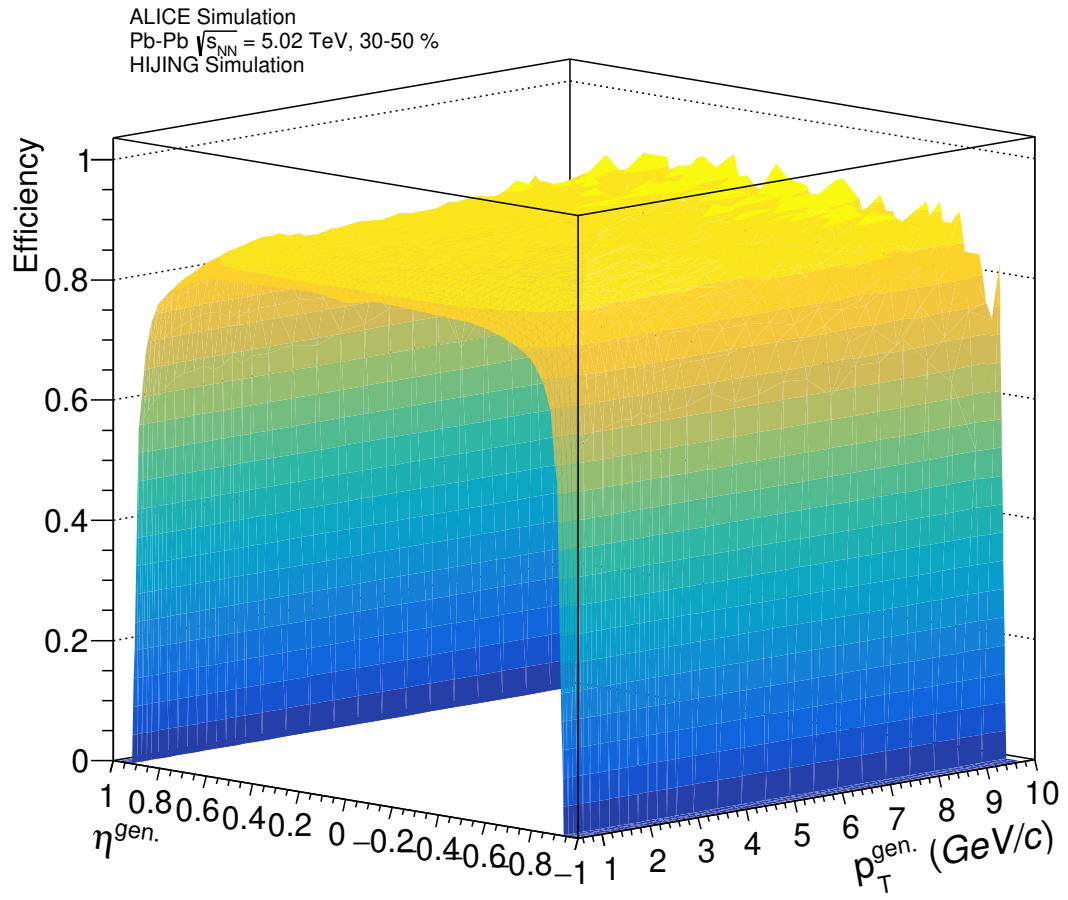
Collision System	Centrality	N_{events}	N_{jets}	$N_{hadrons}$
p-p	-	580M	386,258	427,049
Pb-Pb	0-10%	24M	2,692,627	469,115,437
Pb-Pb	30-50%	36M	2,121,953	123,792,450

apply selection criteria to remove events with pile-up where particles from previous collisions are reconstructed as part of the current event. These selection criteria include correlating the number of tracks in the ITS+TPC with the number of tracks matched to the TOF, correlating the number of tracks in an event with the number of tracks in the TPC, and correlating the number of clusters in the TPC with the number of clusters in the SDD+SSD.

3.1.2 Track Selection

Jet-hadron correlation analyses require tracks to be uniformly reconstructed and have a good momentum resolution. We require the following track selection criteria. Tracks must lie within the acceptance of the TPC, which is $|\eta| < 0.9$. We require that tracks have a minimum p_T of 0.15 GeV/c, and that they have at least 70 TPC space points, or hits left by a charged particle, associated with the track. We require that the track has a χ^2 per degree of freedom less than 4.0, and that the track has been refit using the SPD and ITS detectors.

Tracking inefficiencies include effects from missing tracks that traverse the boundaries of TPC sectors, interactions with the detector causing particles to move outside of the detector acceptance, tracks that are misreconstructed to include points from another particle, and tracks that are missing hits. The single track reconstruction efficiency is defined as the probability that a charged particle produced in the collision will be reconstructed as a track in the detector as a function of p_T and η for each collision system. The single track reconstruction efficiency for this analysis has been determined for the Pb-Pb collisions and is the same as in [86], shown in Figure 3.1. The efficiency is determined using Monte-Carlo simulations of the ALICE detector and the HIJING event generator [87, 88]. Particles are generated and propagated through the detector simulation and the probability of reconstructing those particles is calculated. The efficiency is approximately 80% over most of $p_T - \eta$ space, but drops off at low p_T and large η at the edge of the detector acceptance.



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Figure 3.1: Single track reconstruction efficiency as a function of p_T and η for Pb-Pb collisions. [86]

3.1.3 Cluster Selection

To estimate the neutral component in jets we use the EMCal detector using primarily neutral pions. Many corrections must be applied to the calorimeter data before it can be used to report the neutral component in a jet. Cells in the EMCal supermodules are first grouped into clusters seeding from cells with $E_{cell} > 300$ MeV. Only cells with $E_{cell} > 100$ MeV are considered. We follow the corrections used in [86].

EMCal cells must be calibrated to convert the raw signal into energy. The energy calibration is done iteratively based on the location of the π_0 peak. Bad channels that deviate greatly from the mean cell energy are removed. Signals from each supermodule arrive at the readout electronics at different times, so a time calibration is applied to correct for this. Clusters whose energy is centered around a single cell are removed as exotic clusters, arising from particles striking the avalanche photodiode directly rather than showering in the scintillator. In these cases, the EMCal signal is not an accurate measurement of the particle's energy. The cluster energy is corrected for a non-linear detector response, adjusting both the shape and energy shift. Finally, charged hadrons leave a signal in the EMCal. A correction is applied to adjust clusters that are matched to tracks by subtracting the track momentum. This ensures that the energy from charged hadrons is not double-counted when reconstructing jets.

3.1.4 Jet Selection

Jets are clustered using the anti- k_T algorithm implemented in the FastJet v3.4 software package [52]. We reconstruct jets using tracks and EMCal clusters using the p_T -recombination scheme with a jet resolution parameter of $R=0.2$. This choice of jet radius parameter balances the ability to capture the jet energy while ensuring there are enough jets that fall within our fiducial acceptance.

In order to minimize the impact of combinatorial jets, we only cluster tracks and EMCal clusters with $p_T \geq 3$ GeV/c. Additionally, we require that every jet contain at least one track or cluster with $p_T \geq 5$ GeV/c. These cuts reduce the background

to almost zero at the cost of introducing a bias to our jet population. To correct for the remaining background, we use the ALICE area-based background subtraction method. In this method, we assume that the remaining background contribution to a jet is proportional to the area of that jet. The background momentum density per unit area (ρ) is measured using the k_T jet-finding algorithm which clusters the softest constituents first. It is estimated as the median of the p_T per unit area of k_T jets after throwing out the two highest momentum jets in the event. The background is then subtracted from the jet p_T on a per-jet basis.

We also require that jets pass the following quality cuts. The jet centroid must lie within the EMCal fiducial volume, which is $|\eta| < 0.5$ for jets with $R=0.2$. EMCal clusters that contribute to the jet must have arrived between $-50 \text{ ns} < t_{cluster} < 100 \text{ ns}$. The jet area, A_{jet} , must be greater than $0.6 \pi R^2 \approx 0.075$ for $R=0.2$ to further reduce to contribution from combinatorial jets. Finally, the jet must not contain tracks with $p_T > 100 \text{ GeV}/c$, which are unreliable.

3.1.5 Event Plane Determination

The event plane is determined using the strategy outlined in [83] with a correction implemented from [89]. We determine the second-order event plane, Ψ_2 , using the forward detectors V0A and V0C to avoid correlations with our trigger jets and associated hadrons in the central detectors. First, we define the event flow vector, Q_n , as X and Y components,

$$\begin{aligned} X_n &= Q_n \cos(n\Psi_n) = \sum_i w_i \cos(n\phi_i) \\ Y_n &= Q_n \sin(n\Psi_n) = \sum_i w_i \sin(n\phi_i) \end{aligned} \tag{3.1}$$

where w_i is the weight of the i_{th} particle, ϕ_i is the azimuthal angle of the i_{th} particle, and n is the order of the event plane. The event plane angle is then given by,

$$\Psi_n = \frac{1}{n} \arctan \left(\frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)} \right). \quad (3.2)$$

The event plane is corrected for non-flatness by introducing a correction term and defining a new event plane angle,

$$\Psi_n^{corr.} = \Psi_n + \Delta\Psi_n \quad (3.3)$$

where $\Delta\Psi_n$ is the correction term. The correction term is defined as,

$$\Delta\Psi_n = \sum_n (A_n \cos(n\Psi_n) + B_n \sin(n\Psi_n)). \quad (3.4)$$

A_n and B_n are defined so that the n^{th} Fourier moment of the corrected distribution is zero. Therefore, they can be determined from the original distribution by,

$$\begin{aligned} A_n &= -\frac{2}{n} \langle \sin(n\Psi_n) \rangle \\ B_n &= \frac{2}{n} \langle \cos(n\Psi_n) \rangle \end{aligned} \quad (3.5)$$

where the brackets indicate event-averages.

3.2 Jet-hadron Correlation Functions

Jet-hadron correlation functions measures the density of hadrons per jet in $(\Delta\phi, \Delta\eta)$, where $\Delta\eta = \eta - \eta_{jet}$ and $\Delta\phi = \phi - \phi_{jet}$. The jet-hadron correlation function is defined as

$$\rho_{corr.}(\Delta\eta, \Delta\phi) = \frac{1}{N_{jets}} \frac{d^2 N_{assoc.}}{d\Delta\eta d\Delta\phi} \quad (3.6)$$

Table 3.2: Jet momentum and associated hadron momentum bins used in this analysis.

Jet Momentum Bins	Associated Hadron Momentum Bins
20-40 GeV/c	1-1.5 GeV/c
40-60 GeV/c	1.5-2 GeV/c
	2-3 GeV/c
	3-4 GeV/c
	4-5 GeV/c
	5-6 GeV/c
	6-10 GeV/c

where N_{jets} is the number of jets, and $N_{assoc.}$ is the number of hadrons associated with a jet. The jet-hadron correlation function is usually measured in bins of jet momentum and associated hadron momentum, summarized in Table 3.2.

The jet-hadron correlation function are corrected for single-track reconstruction and pair acceptance inefficiencies by

$$\rho_{corr.}(\Delta\phi, \Delta\eta) = \frac{\rho_{corr.}^{meas.}(\Delta\eta, \Delta\phi)}{\epsilon_{single}(\eta_{assoc.}, p_{T,assoc.})\epsilon_{pair}(\Delta\phi, \Delta\eta, p_{T,assoc.}, p_{T,jet})} \quad (3.7)$$

where ϵ_{single} is the single track reconstruction efficiency, and ϵ_{pair} is the pair acceptance efficiency.

There are three regions of interest in jet-hadron correlations, they are detailed in Table 3.3. Around $(\Delta\eta, \Delta\phi) = (0,0)$ the jet-hadron correlation function is dominated by hadrons associated with the trigger jet. On the other side, π radians away in $\Delta\phi$ from the jet peak, the jet-hadron correlation function is dominated by hadrons that are likely related to the back-to-back pair jet that must exist by momentum conservation. We call these regions the near-side and away-side regions, respectively. The third region is the background-dominated region, whose hadrons are not correlated with any jet. An illustration of a typical jet-hadron correlation function with the regions of interest highlighted is shown in Figure 3.2.

3.2.1 Pair Acceptance Efficiency

The pair acceptance efficiency is defined as the probability that a jet-hadron pair will be reconstructed at a particular $\Delta\phi$, $\Delta\eta$, jet p_T and associated hadron p_T . In this analysis we use a mixed event technique to calculate the pair acceptance efficiency. In this technique, we accumulate the hadrons in every event processed, forming a super event. Then, we compute the mixed event correlations between jets in new events and hadrons in the super event. Once normalized, the mixed event correlations are the pair acceptance efficiency, ϵ_{pair} .

Table 3.3: Regions of interest in jet-hadron correlations.

Region	$\Delta\eta$	$\Delta\phi$
Near-side	$ \Delta\eta \leq 0.8$	$ \Delta\phi \leq \pi/2$
Away-side	$ \Delta\eta \leq 0.8$	$\pi/2 \leq \Delta\phi \leq 3\pi/2$
Background	$0.8 \leq \Delta\eta \leq 1.2$	$-\pi/2 \leq \Delta\phi \leq \pi/2$

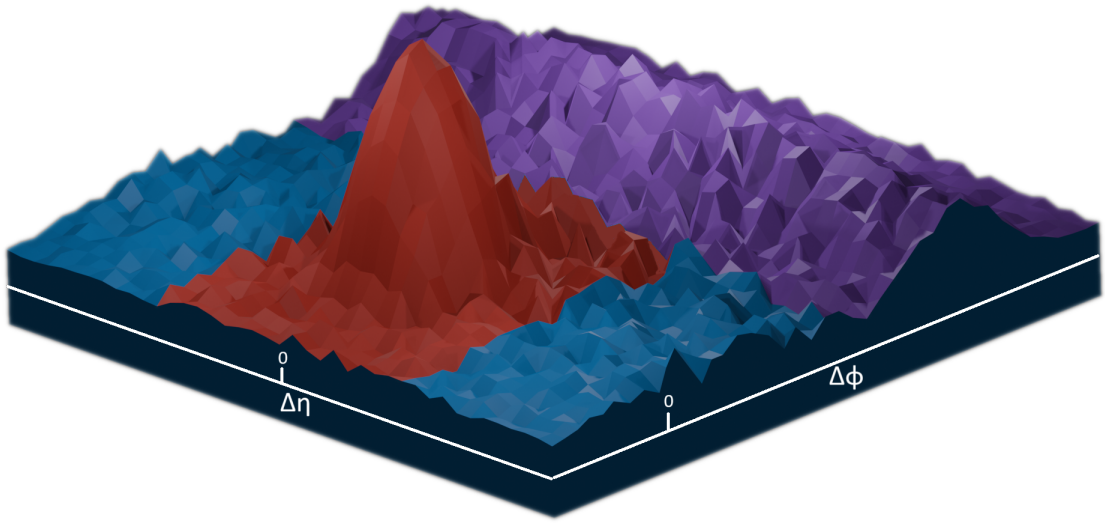


Figure 3.2: Illustration of a prototypical jet-hadron correlation function. The near-side is highlighted in red, the away-side in purple, and the background-dominated in blue. Jet-hadron correlations vary greatly with $p_T^{assoc.}$ and so will differ from the figure.

Our mixed events are constructed by taking each event that is processed and adding all of its tracks to a super event depending on event multiplicity and z-vertex position. A single track reconstruction efficiency is applied to the tracks that are added so that the resulting distribution is comparable to the raw correlations that have already been corrected for the single track reconstruction efficiency. Once a super event contains a pre-specified minimum number of tracks, we calculate the correlations between jets in each new event and all tracks from previous events with a matching multiplicity and z-vertex position.

Before we can use the mixed event correlation function as a pair acceptance efficiency, we need to normalize it. We assume that the mixed event correlation function will have its peak around $\Delta\eta = 0$. This is because we have full pair acceptance in this region. This normalization can be done in several ways [85]. We use a sliding window approach over $\Delta\phi$. In order to perform the sliding window technique, we restrict our mixed event correlations to a small window in $\Delta\eta$ where the mixed event correlations are roughly flat and project onto $\Delta\phi$. We used $|\Delta\eta| \leq 0.3$. We then compute the sliding average over $\Delta\phi$ using a window of size $\pi/2$ to determine the maximum of the un-normalized mixed event correlations. The sliding window average is less susceptible to statistical fluctuations than simply taking the maximum over $\Delta\phi$.

3.2.2 Background Estimation

Jet-hadron correlations have a background from non-jet related processes that needs to be estimated. The background arises from many physical processes and has a different shape in p-p collisions as compared with Pb-Pb collisions. In p-p collisions, the background is relatively flat in $(\Delta\phi, \Delta\eta)$, allowing it to be modeled as a simple pedestal. In Pb-Pb collisions, the background is flat in $\Delta\eta$, but not in $\Delta\phi$ and must be estimated from the data. The background is estimated from the background-dominated region. The procedures for estimating the background are described in the following sections.

p-p Background

In p-p collisions, the background level is estimated by taking the average in the background-dominated region. This is done by integrating the jet-hadron correlation function over that region and dividing by the area of the region in $(\Delta\phi, \Delta\eta)$.

Pb-Pb Background

In Pb-Pb collisions, the presence of flow results in azimuthal anisotropies in the background. We use the reaction plane fit(RPF) method to estimate the background in the presence of a flow-correlated background [90]. The RPF method leverages the dependence of a jet on its angle with respect to the reaction plane to provide tangible formulas describing the flow-correlated background with respect to $\Delta\phi$ [91]. Because the background does not depend on $\Delta\eta$, we integrate it out of the background dominated region,

$$\rho_{corr.}^{bkg.}(\Delta\phi) = \frac{1}{0.4} \int_{0.8}^{1.2} \rho_{corr.}(\Delta\phi, \Delta\eta) d\Delta\eta + \frac{1}{0.4} \int_{-1.2}^{-0.8} \rho_{corr.}(\Delta\phi, \Delta\eta) d\Delta\eta. \quad (3.8)$$

By fixing the angle of a jet to a range relative to the reaction plane, we can express the background as [91, 90],

$$b(\Delta\phi, \Psi^t) = \frac{dN^{pairs}}{\pi d\Delta\phi} = \tilde{\beta} \left(1 + \sum_{n=1}^{\infty} 2\tilde{v}_n^t \tilde{v}_n^a \cos(n\Delta\phi) \right) \quad (3.9)$$

where N^{pairs} is the number of associated hadrons correlated with the jet, $\tilde{v}_n^t$, and $\tilde{v}_n^a$ are the jet and associated hadron effective v_n . $\tilde{\beta}$ is the effective background level given by,

$$\tilde{\beta} = B \left(1 + \sum_{k=2,4,6,\dots} 2v_k \cos(k\phi_s) \frac{\sin(kc)}{kc} R_k \right). \quad (3.10)$$

B is a fitting parameter controlling the level of the background, R_k is the reaction plane resolution for the k_{th} order reaction plane. ϕ_s is the center of the range that the jet azimuthal angle is fixed in and c is the width of that range. The effective v_n for jets is given by,

$$\tilde{v}_n^t = \frac{v_n + \cos(n\phi_s) \frac{\sin(nc)}{nc} R_n + \sum_{k=2,4,6,\dots} (v_{k+n} + v_{|k-n|}) \cos(k\phi_s) \frac{\sin(kc)}{kc} R_k}{1 + \sum_{k=2,4,6,\dots} 2v_k \cos(k\phi_s) \frac{\sin(kc)}{kc} R_k}. \quad (3.11)$$

We restrict our jet azimuthal angles to three ranges relative to the event plane to constrain the RPF parameters, shown in Figure 3.3. In-plane jets lie in the range defined by $\phi_s = 0$, $c=\pi/6$, and out-of-plane jets lie in the range defined by $\phi_s = \pi/2$, $c=\pi/6$. Mid-plane jets lie in either of the ranges defined by $\phi_s = \pi/4$, $c=\pi/12$ and $\phi_s = 3\pi/4$, $c=\pi/12$. We simultaneously fit the background-dominated region for hadrons associated with in-, mid-, and out-of-plane jets using the curve fit function from the python package scipy [92]. The errors are computed by inverting the estimated Hessian matrix at the optimal parameter values. The fit parameters are B, v_2^t , v_2^a , $(v_3^t * v_3^a)$, v_4^t , and v_4^a . The product of first-order flow coefficients, $(v_1^t * v_1^a)$, is kept fixed at zero, due to the fact that v_1^t is very likely zero [91] and that fitting the interval $-\pi/2 \leq \Delta\phi \leq \pi/2$ alone will not constrain its value well. As a cross-check, the product was allowed to vary and the resulting optimal values were always within uncertainty of zero. Because of the periodic nature of the Fourier decomposition, we can safely extrapolate the background from the fitting region on the near-side to the away-side.

3.3 Particle Identification

In this analysis we use the TPC and the TOF to determine the particle fractions for each region of interest in the jet-hadron correlation function. This is done by modeling the statistical distribution of each species in the TPC signal and calibrating the distributions using the TOF signal. Figure 3.4 shows the π to K and K to p

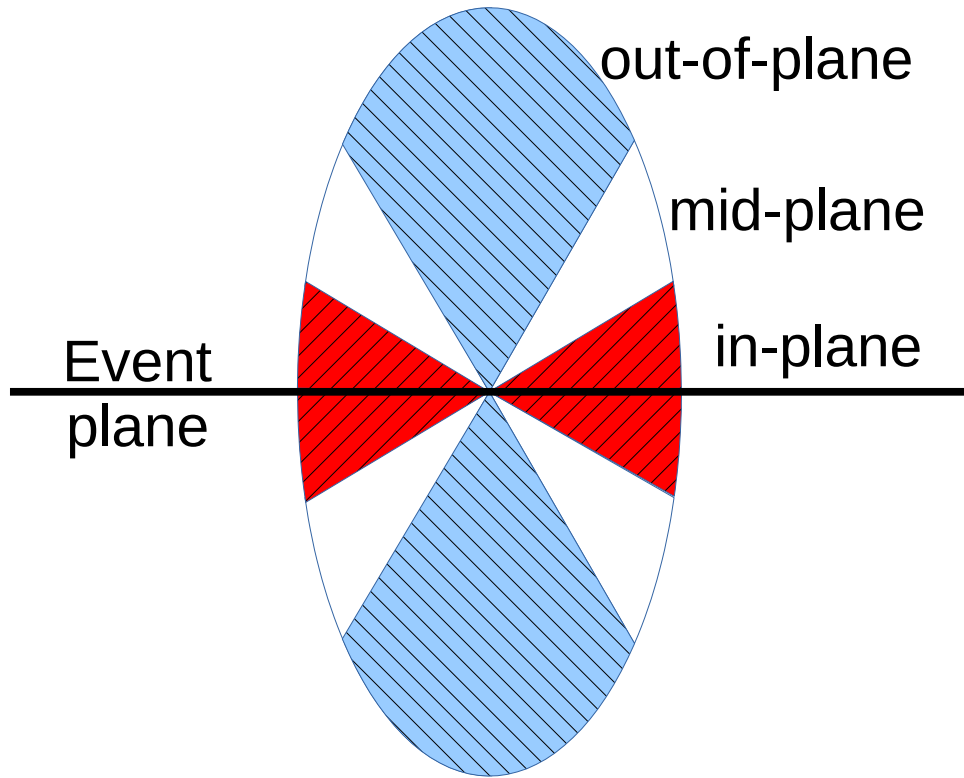


Figure 3.3: Ranges of jet azimuthal angles relative to the reaction plane used in the RPF method.

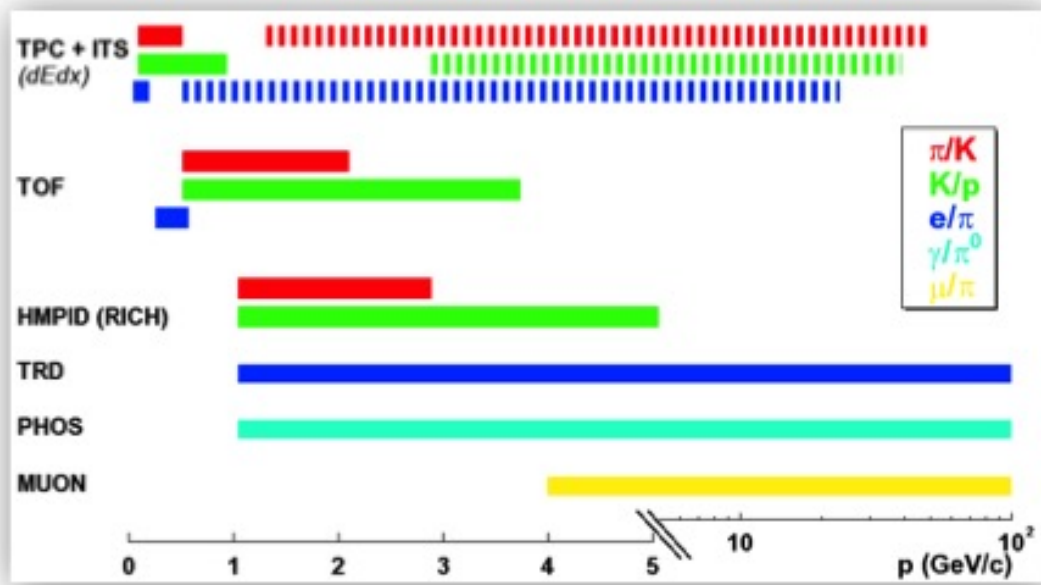


Figure 3.4: Particle identification ranges for the TPC and TOF detectors in ALICE [93].

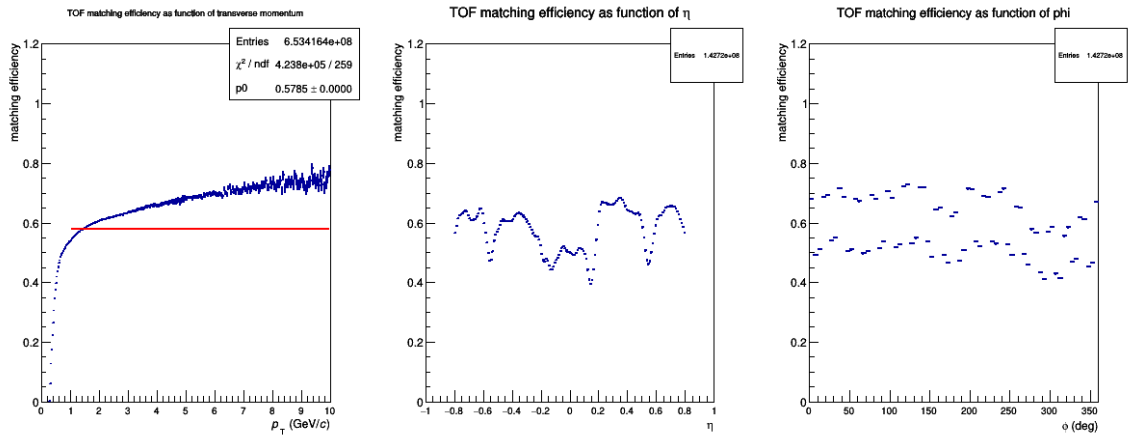


Figure 3.5: Efficiency of matching TPC tracks to the TOF for one run of data used in this analysis. This is representative of the entire dataset.

separation for the detectors in ALICE. The TPC can cleanly separate kaons and pions up to 0.5 GeV/c, and kaons and protons up to 1 GeV/c. The TOF can cleanly separate kaons and pions up to 2 GeV/c and kaons and protons up to 4 GeV/c. Above these momenta, a bayesian technique can be used to statistically estimate the distribution of each species. Typically, a hybrid approach is used, choosing the best technique per momentum bin. However, in order to use the TOF signal, the particle must leave a signal in the TOF that is matched to a track in the TPC. The efficiency of matching TPC tracks to the TOF is shown in Figure 3.5 for a single run in the data used for my analysis. The matching efficiency is approximately 65% for tracks above 1 GeV/c, but its shape in η , and ϕ is not uniform and must be accounted for when considering correlations. These nonuniformities arise primarily because of the material budget, in particular the TRD modules between the TOF and the TPC. Because the TOF matching efficiency is not uniform, using only tracks which have an associated TOF signal to construct our jet-hadron correlations would require a correction for this matching efficiency, and the pair acceptance correction needs to be recomputed. In this analysis, we propose an alternative method. First we look at the TPC $\frac{dE}{dx}$ for all tracks in a particular region of interest. For those tracks with a TOF signal we apply 2σ selections around the mean time-of-flight for each particle species to sample each species preferentially. We then fit the TPC $\frac{dE}{dx}$ distribution for each sample to find the most likely shape of the distribution for each species. Finally, we fix the most likely shapes and find the absolute levels for each species' distribution in the track inclusive TPC $\frac{dE}{dx}$ distribution. This method has the advantage of not requiring a correction for the TOF matching efficiency, while still maintaining the ability to constrain the shape of the TPC $\frac{dE}{dx}$ distribution for each species with the TOF signal. This method can be applied regardless of the associated hadron momentum to estimate the statistical distributions of each species for all tracks.

3.3.1 Particle Identification in the TPC

The specific energy loss per unit length as a function of momentum is shown for the TPC in Figure 3.6. For each momentum bin, we take the $\frac{dE}{dx}$ signal for each track and compute the number of standard deviations away from the mean energy loss for a pion. We then model that distribution as a mixture of a Gaussian and two generalized Gaussians for pions, kaons, and protons, respectively. Pions are distributed with a mean $\mu_\pi=0$ and width $\sigma_\pi=1$. Kaons and protons are distributed according to generalized Gaussians with a skewness parameter, α , which is fixed to 0 above 1.5 GeV/c, and are otherwise well described by a standard Gaussian. The overall mixture model is given as,

$$f(x) = w_\pi \mathcal{N}(\mu_\pi, \sigma_\pi) + w_K \mathcal{G}(\mu_K, \sigma_K, \alpha_K) + w_p \mathcal{G}(\mu_p, \sigma_p, \alpha_p) \quad (3.12)$$

where w_π , w_K , and w_p are the fractions of pions, kaons, and protons, respectively. The parameters μ_π , σ_π , μ_K , σ_K , α_K , μ_p , σ_p , and α_p are referred to as shape parameters and should depend only on the details of the TPC. The typical Gaussian distribution is given by,

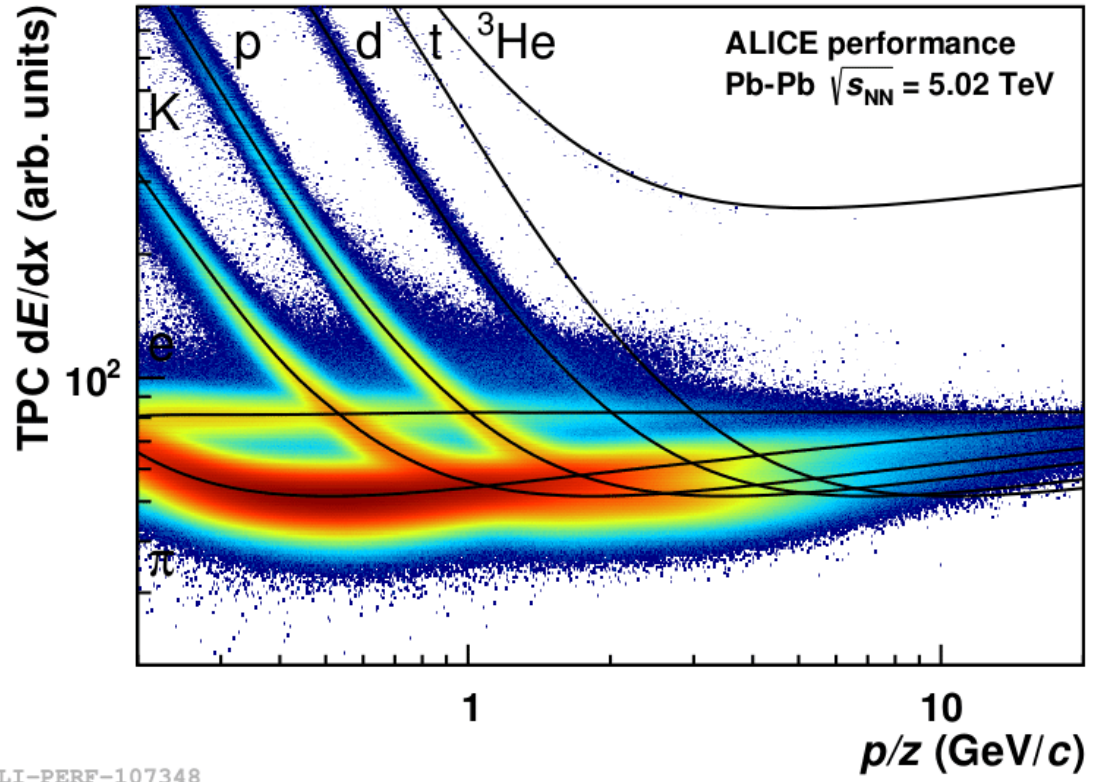
$$\mathcal{N}(\mu_\pi, \sigma_\pi) = \frac{1}{\sqrt{2\pi}\sigma_\pi} e^{-\frac{(x-\mu_\pi)^2}{2\sigma_\pi^2}}, \quad (3.13)$$

and the generalized Gaussian distribution is given by,

$$\mathcal{G}(\mu, \sigma, \alpha) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \left(\alpha \frac{x-\mu}{\sigma} \right) \quad (3.14)$$

3.3.2 Particle Identification in the TOF

The TOF detector provides a time-of-flight measurement for each track. The time-of-flight is the time it takes for a particle to travel from the primary vertex to the TOF detector. The time-of-flight is given by



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Figure 3.6: Specific energy loss per unit length as a function of momentum for the TPC in Pb-Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV.

$$t = t_{TOF} - t_{start} = \frac{L}{\beta c}, \quad (3.15)$$

where t_{TOF} is the time the particle arrives at the TOF, t_{start} is the time of the collision as measured by the T0 detector, L is the distance between the primary vertex and the TOF, β is the velocity of the particle in units of the speed of light, and c is the speed of light. The time-of-flight measurement has a resolution of approximately 120 ps. The TOF signal is typically represented in terms of β given as

$$\beta = \frac{L}{c(t_{TOF} - t_{start})}. \quad (3.16)$$

The distribution of β as a function of momentum is shown in Figure 2.13. The mean β for each species can be derived from kinematics and the standard deviations depend on the detector performance.

3.3.3 Particle Species Calibration

In order to estimate the particle fractions in each region, we employ a two-step process. First, we make three subsamples of tracks, preferentially selecting pions, kaons, and protons with a 2σ restriction around the respective means in the TOF signal. The resulting distributions in the TPC signal for each subsample and the inclusive sample are shown in Figure 3.7 for semicentral Pb-Pb collisions with $3 < p_T^{assoc.} < 4$ GeV/c on the near-side signal region. These four distributions are fit simultaneously, sharing the shape of each species' TPC $n\sigma_\pi$ distribution with separate amplitudes for each subsample. This fit is also shown in Figure 3.7. The subsamples of pions, kaons, and protons are used to calibrate the shapes of each distribution. The distributions' shape parameters are then fixed and another fit of only the track inclusive TPC signal, shown in Figure 3.7d, is performed to find the particle fractions. The particle fractions for 30-50% central Pb-Pb collisions are shown in Figure 3.8. Fit parameters for each hadron momentum bin are shown in Appendix B.

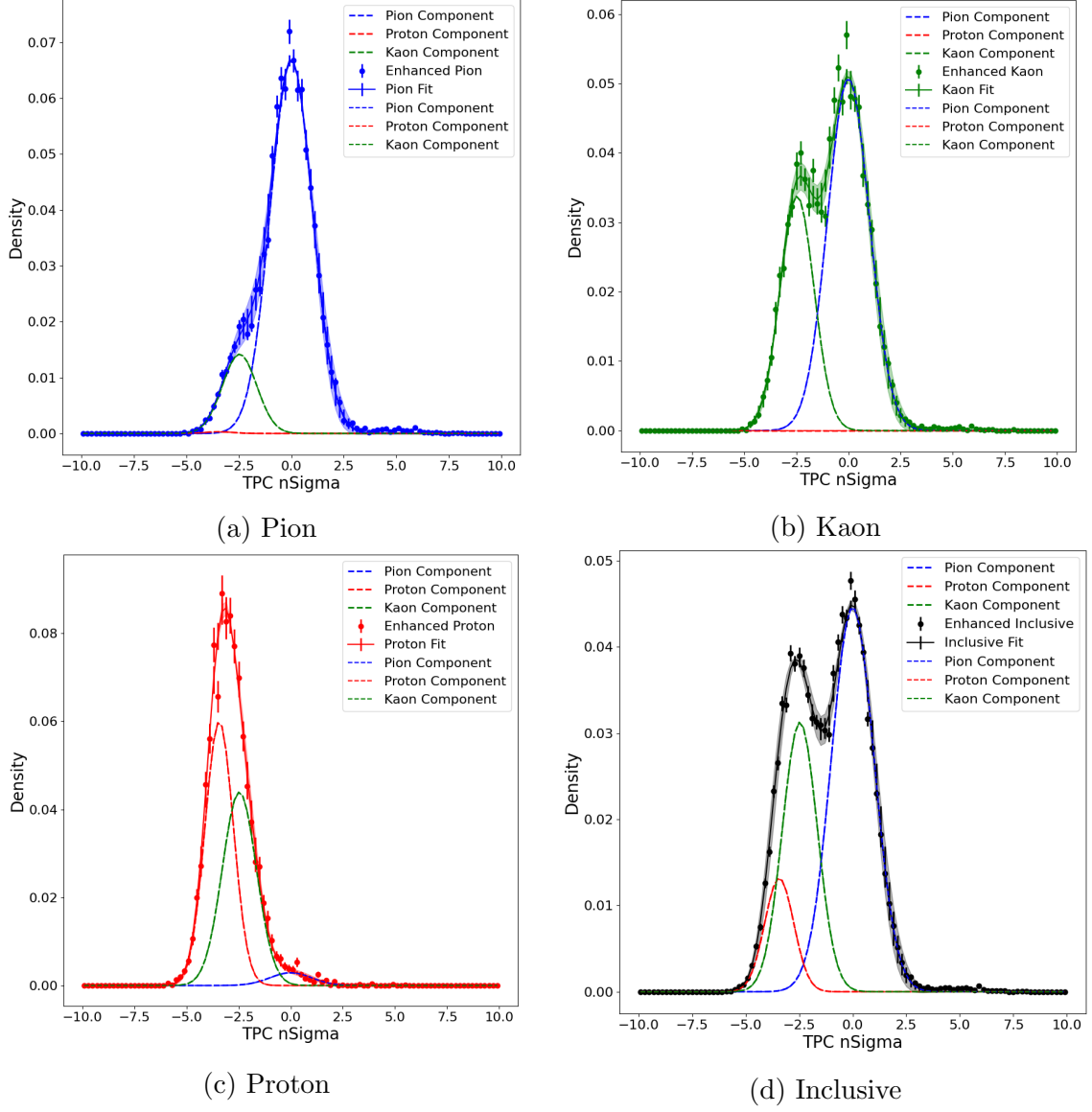
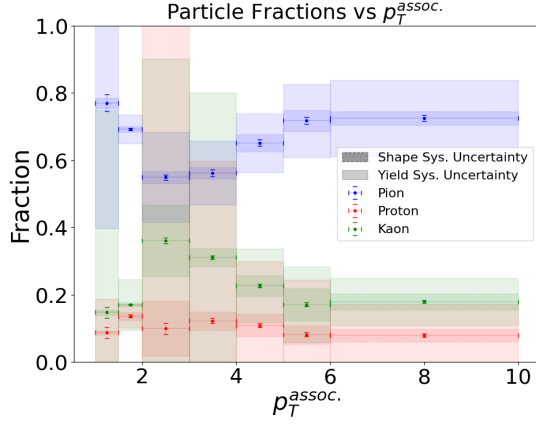
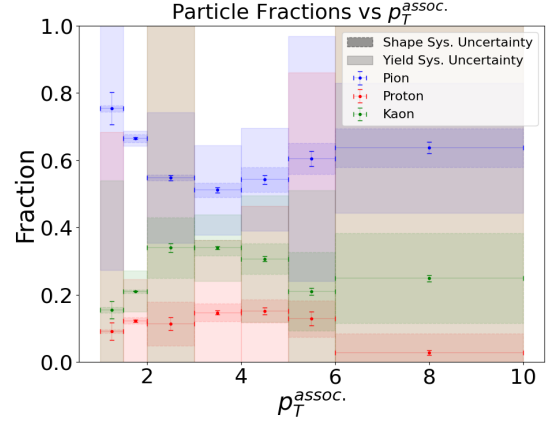


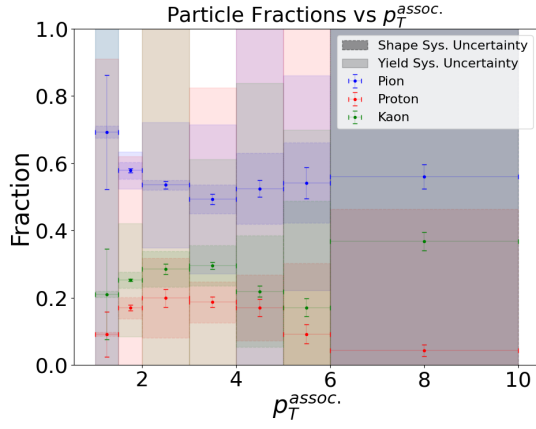
Figure 3.7: Number of standard deviations away from the pion mean in TPC $\frac{dE}{dx}$. The inclusive sample is all particles measured in the TPC, and each species is the subsample which preferentially samples that species.



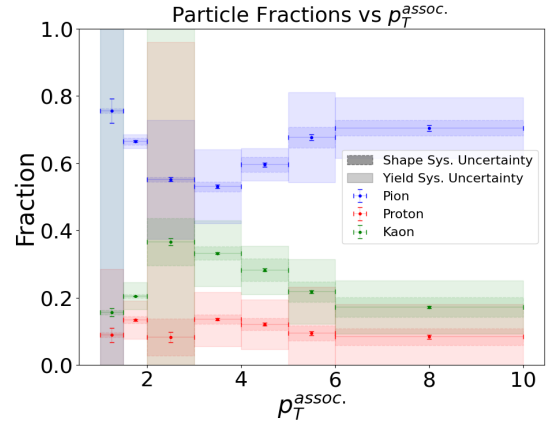
(a) Near-side



(b) Away-side



(c) Background



(d) All regions

Figure 3.8: Particle fractions for each species in the near-side, away-side, background and inclusive regions. These are for semicentral Pb-Pb collisions.

3.4 Systematic Uncertainties

There are several systematic uncertainties that contribute to the final result. They are shown in Figures 3.9, 3.10 for semicentral collisions and Figures 3.11, 3.12 for central collisions. The dominant uncertainties are due to the determination of the particle fractions. To evaluate this uncertainty, we split our data into eight independent groups and determine the particle fractions for each group. The results are averaged and the standard deviation is taken as the systematic uncertainty. We also report the combined systematic uncertainty due to varying the optimal fit parameters within the parameter covariance matrix for each group individually. These uncertainties are largely driven by the non-convex nature of fitting an ill-separated gaussian mixture model, and tend to improve when a better initial parameter guess is provided. In Pb-Pb, the RPF method introduces a correlated systematic uncertainty which is estimated from the parameters found in the RPF fit along with the covariance matrix. Additionally, it is known that pions, kaons and protons have different v_n [94], though our analysis does not have the statistics to resolve this. Because our jet-hadron regions are defined on $\Delta\phi = (-\pi/2, \pi/2)$ and $\Delta\phi = (\pi/2, 3\pi/2)$, contributions from even v_n are integrated out. Therefore, to estimate the uncertainty this introduces, we vary the odd v_n found in the particle-agnostic RPF fit up to the values measured in [94] and take the difference as the systematic uncertainty.

The single particle reconstruction efficiency introduces a systematic uncertainty due to imperfections in the simulation used to calculate them. In particular, the description of the material budget and hadronic interaction cross-section are imperfect. We use the values determined in [8], taking the largest value in the range when there is a dependence on hadron momentum. This results in an overall uncertainty of roughly 4% and 5% for kaons and protons respectively. The pair acceptance efficiency has two sources of uncertainty. The first is a dependence on z-vertex position, and the second is the normalization technique used. To estimate the uncertainty due to the z-vertex dependence we bin the jet-hadron correlations

and the mixed event correlations in z-vertex position and repeat the analysis for each bin. The standard deviation of the results is taken as the systematic uncertainty. We estimate the normalization uncertainty by varying the normalization technique and taking the difference as the systematic uncertainty.

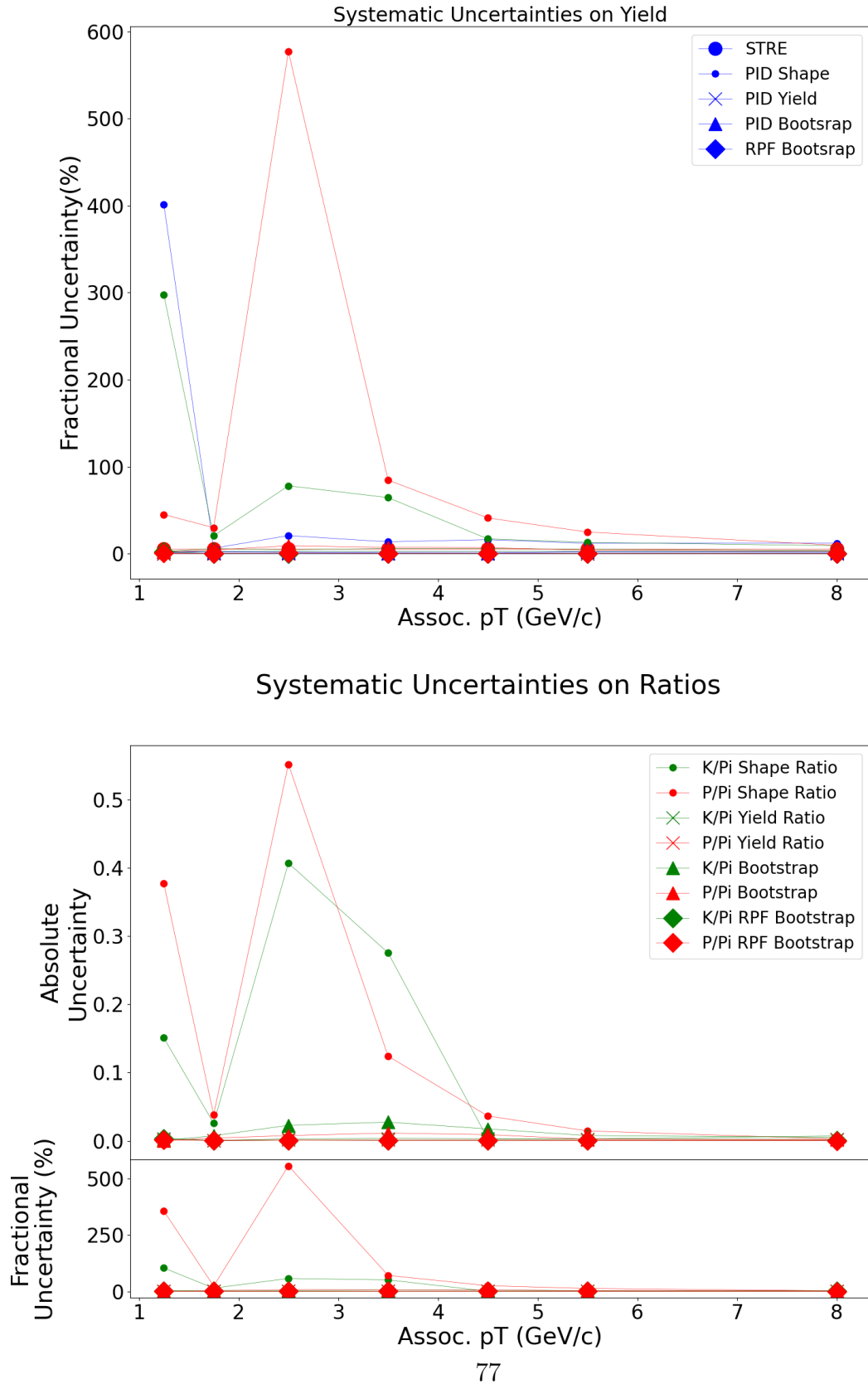


Figure 3.9: Systematic uncertainties by p_T for semicentral collisions in the near-side region

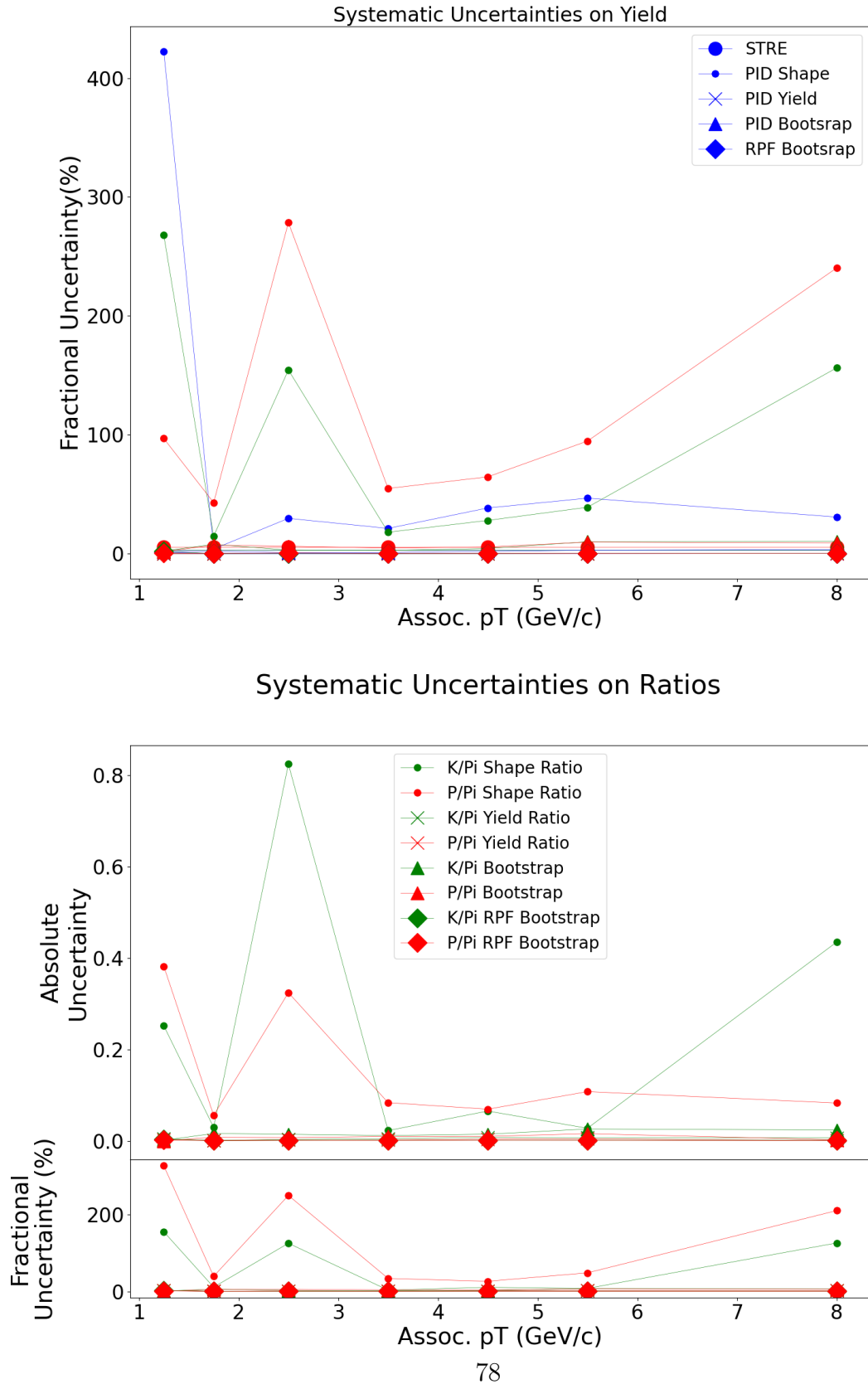


Figure 3.10: Systematic uncertainties by p_T for semicentral collisions in the away-side region

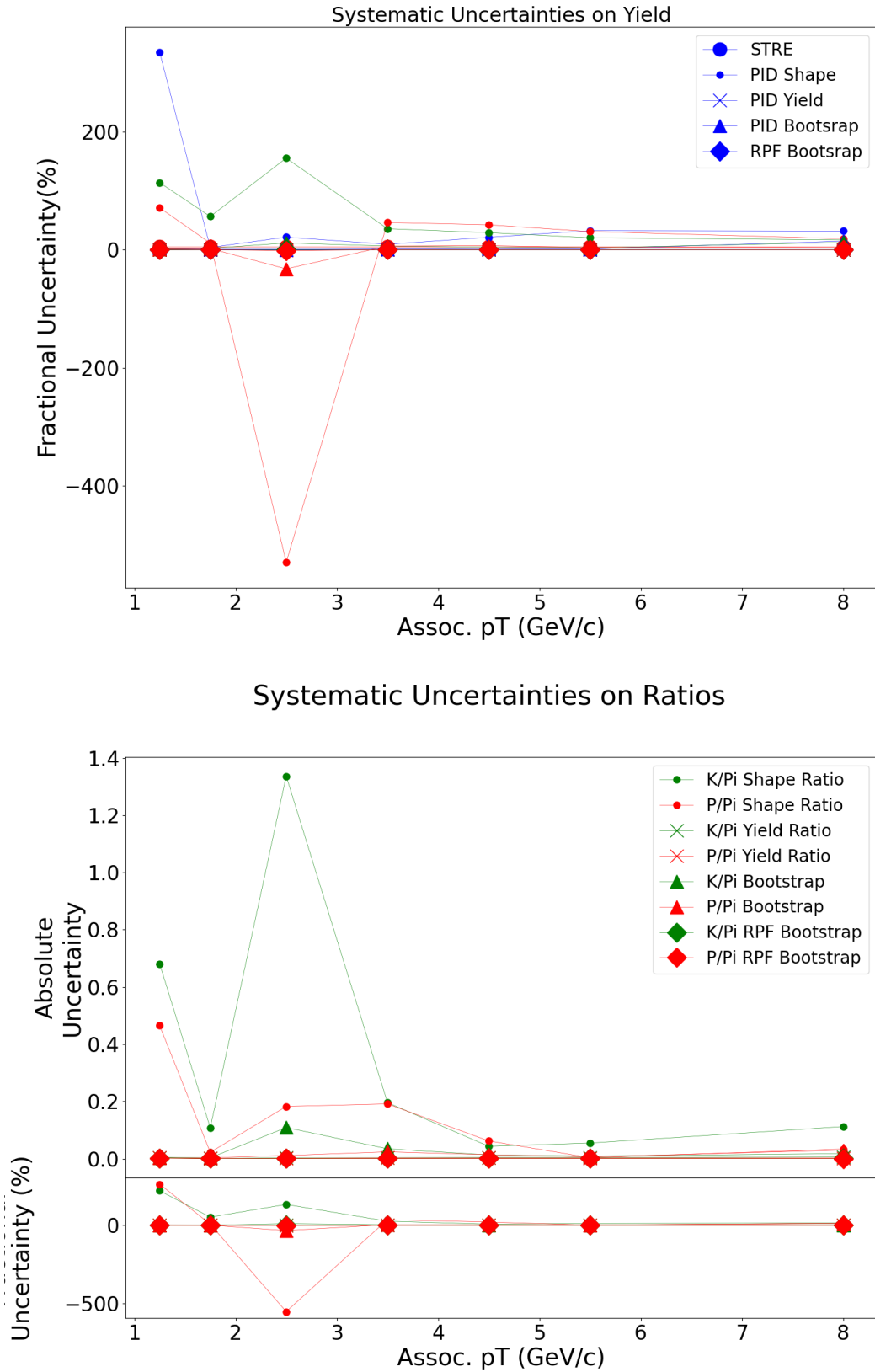


Figure 3.11: Systematic uncertainties by p_T for central collisions for near-side region

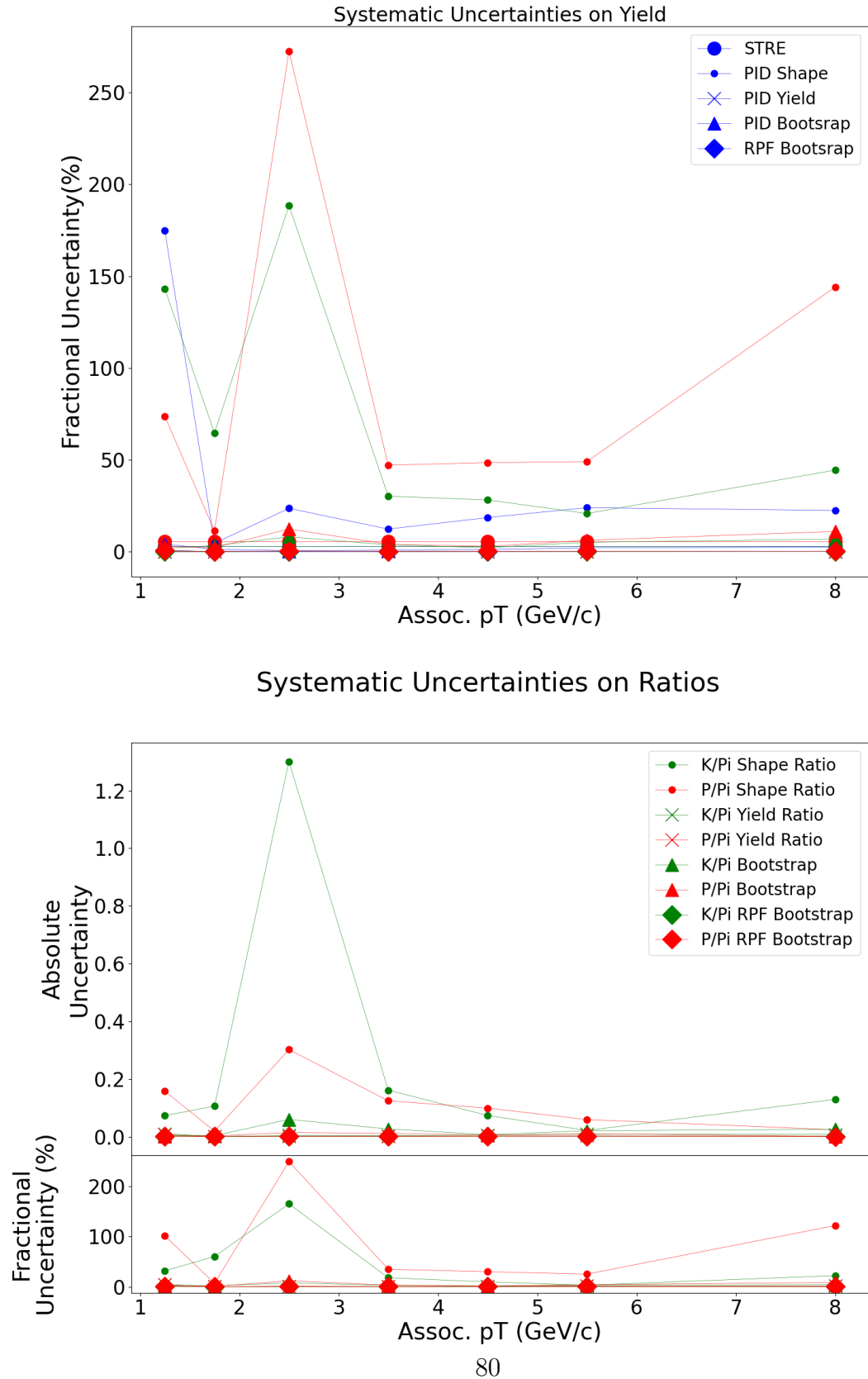


Figure 3.12: Systematic uncertainties by p_T for central collisions for away-side region

Chapter 4

Results and Conclusions

The background-subtracted, per-trigger yields are measured for pions, kaons, and protons in the near-side and away-side regions of the jet-hadron correlation function using reconstructed jets with $20 \text{ GeV}/c < p_T < 40 \text{ GeV}/c$ from Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$, and the ratios of the yields of kaons to pions and protons to pions are computed.

4.1 Yields

The per-trigger yields for each species are estimated by taking the inclusive yield and scaling it by the particle fractions (Figure 3.8) found in each region-of-interest. We estimate the per-trigger yields in the background region using the RPF method and scaling by the particle fractions. The per-trigger, background-subtracted yields for each species are shown in Figure 4.1 for semicentral collisions and Figure 4.2 for central collisions. The systematic errors from the determination of the particle fractions are shown as rectangles around the data points and constitute the dominant source of uncertainty. We include the per-event inclusive charge-hadron yields for comparison [8].

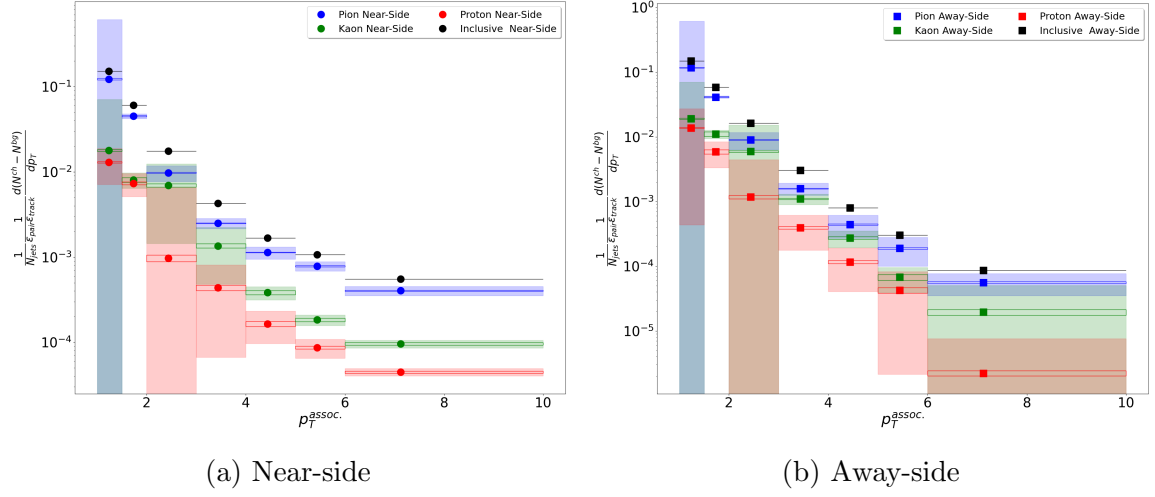


Figure 4.1: Background subtracted yields for each species in the near-side and away-side regions for 30–50% central Pb-Pb collisions. Inclusive identified charged hadron yields are included from [8].

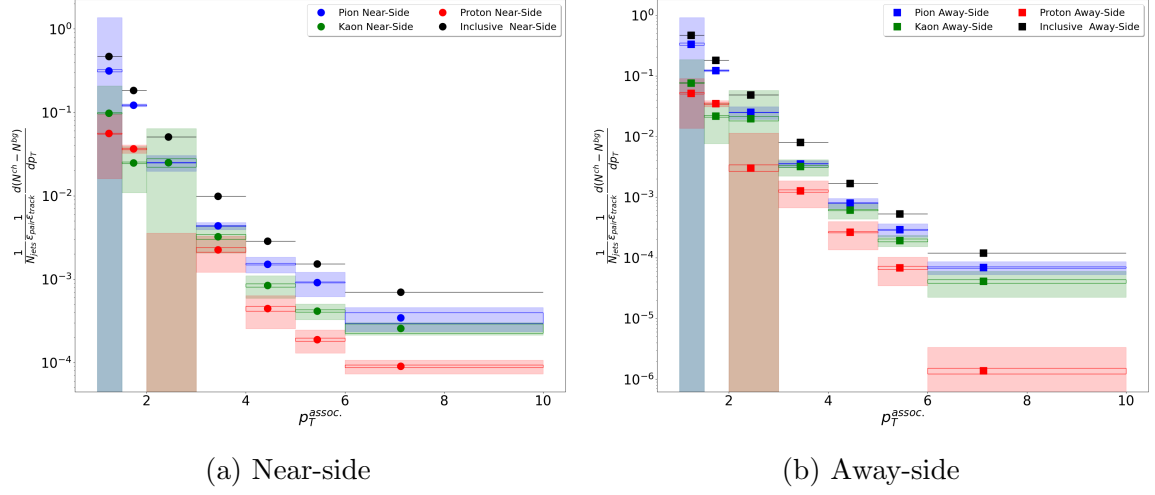


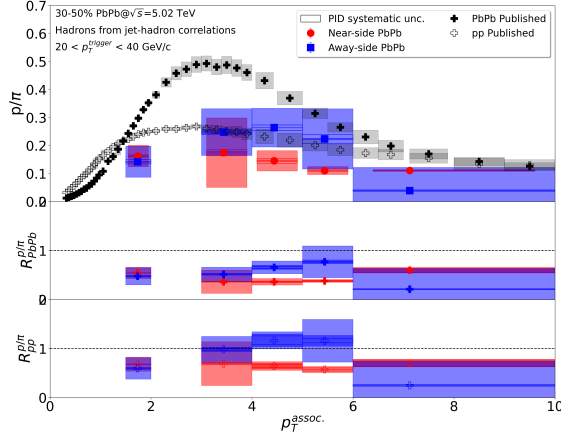
Figure 4.2: Background subtracted yields for each species in the near-side and away-side regions for 0–10% central Pb-Pb collisions. Inclusive identified charged hadron yields are included from [8].

4.2 Ratios

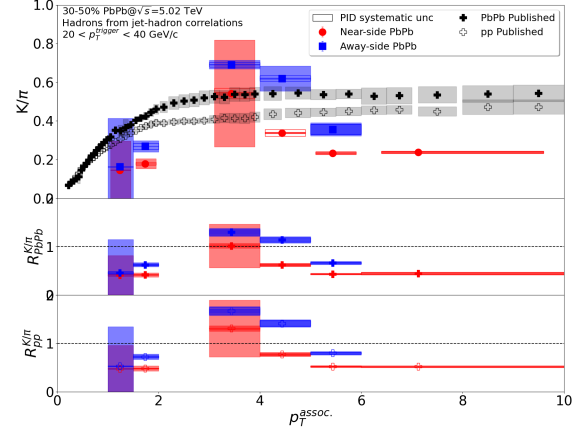
The ratios of the per-trigger yields for kaons to pions and protons to pions provide insight into modifications to strangeness and baryon production in jets. The ratios on both the near-side and the away-side are shown in Figure 4.3 for semicentral collisions and Figure 4.4 for central collisions. Systematic errors from the determination of the particle fractions are shown as open rectangles around the data points. We include the per-event inclusive charge-hadron ratios for comparison [8].

The proton to pion ratio is consistent with that found in proton-proton collisions with the ALICE experiment [8] and RHIC [12, 14] for both the near-side and away-side regions. This indicates that the ratio of baryons to mesons in jets is not significantly modified by the medium. This can be understood by noting that baryon production via recombination requires three partons to be nearby in phase space. While partons forming a jet are spatially close to the partons in the medium, their large transverse momentum is very different than that of partons in the medium, so recombination is unlikely. We also see some minor differences between the near-side and away-side regions around $p_T=3$ GeV/c, but these differences are within the uncertainties.

The kaon to pion ratio tells a much different story. The near-side ratio is consistent with that found in heavy-ion collisions for $2 < p_T < 4$ GeV/c, but quickly falls off above 4 GeV/c. The away-side ratio is consistent with that found in heavy-ion collisions above 2 GeV/c, and even shows signs of enhancement over heavy-ion collisions between 3 and 4 GeV/c. Strangeness in the QGP is expected to be enhanced because the temperature of the QGP is much higher than the mass of the strange quark, so the production of strange quarks is possible via thermal processes. The fact that the ratios are consistent with that found in heavy-ion collisions indicates that jets interact strongly with the QGP, and that the away-side jet interacts more than the near-side jet. The enhancement of the away-side ratio above heavy-ion collisions is surprising, and we do not understand the mechanism driving it.

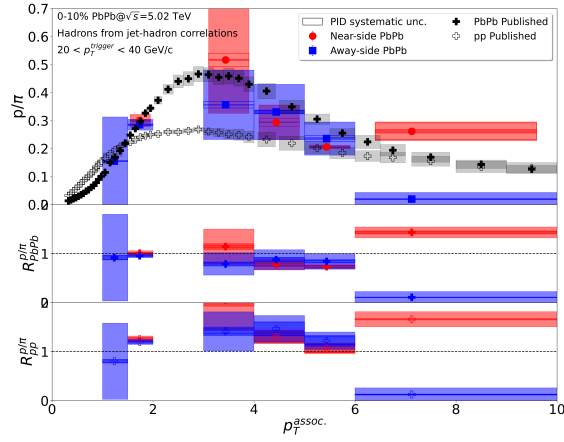


(a) Proton to pion ratio

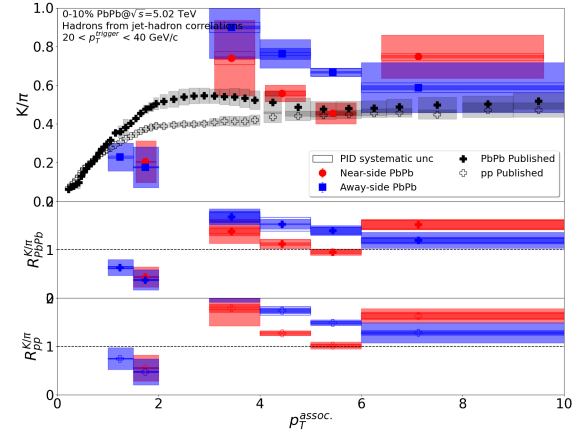


(b) Kaon to pion ratio

Figure 4.3: Ratios of yields for each species in the near-side and away-side regions for 30–50% central Pb-Pb collisions. Near-side errors are scaled in p_T for clarity.



(a) Proton to pion ratio



(b) Kaon to pion ratio

Figure 4.4: Ratios of yields for each species in the near-side and away-side regions for 0–10% central Pb-Pb collisions. Near-side errors are scaled in p_T for clarity.

4.3 Conclusions and Discussion

Strangeness enhancement may be a key signature for jet quenching in heavy-ion collisions [95, 58]. Jets seem to interact strongly with the medium, producing many more strange quarks than would have been created in the vacuum. Surprisingly, it appears that strangeness in jets on the away-side is enhanced above the medium itself. Two possibilities are proposed. The first is that the away-side jet traverses more QGP than the near-side jet, and therefore has more time to interact with the medium. The second is that the away-side jet is more likely to be a gluon jet, which may interact differently with the QGP than a quark jet. We think the former theory is more closely aligned with the results as we expect that strangeness production will not be significantly enhanced in gluon jets over quark jets. This is because producing a strange meson requires a strange-anti-strange pair to be produced. We think that the strangeness enhancement is likely due to interactions with the medium, a significant fraction of which is strange [24].

There are many improvements that can be undertaken for a more precise result. The dominant source of uncertainty is the determination of the particle fractions, which we believe can be improved considerably. In all of the results we have two uncertainties from the PID fitting procedure, one for the distribution shape determination, and another for the yield determination of each species. The uncertainty due to the shape determination is much larger than the uncertainty from the yield determination, and is largely dependent on the resolution and specific energy loss of the TPC. We believe that a detailed simulation of identified jet-hadron correlations in a tool like GEANT could all but remove the uncertainty due to the shape determination. Using the typical ALICE PID techniques from [8], for example, it may be possible to recover similar uncertainties as in that publication, but there are a number of steps to make this possible. Critically, we need to compute the jet-hadron correlations which limits the available statistics dramatically, though this could be alleviated by considering only charged jets, jets that are reconstructed

using the TPC only. These techniques also use several additional PID detectors in the ALICE experiment, each with their own acceptance and resolution. A careful determination of the single track and pair reconstruction efficiencies would need to be undertaken to make this possible, in addition to a careful treatment of the complicated pseudorapidity dependence of the TOF and EMCal.

To better capture the spatial variations in particle composition, it could be interesting to use finer regions-of-interest in $\Delta\eta$ and $\Delta\phi$. This would allow us to investigate the composition of the jet core and the wide-angle composition separately. It is proposed, for instance, that the hadrons resulting from jet-medium interactions are more likely to be produced at wide angles. One could imagine a scenario where the strangeness enhancement disappears at the core. This would be a strong indication that the enhancement is due to multiple interactions with the medium, rather than modifications to fragmentation.

The assumption that the particle composition is the same from event-to-event relative to the jet-hadron correlation region-of-interest ignores potentially large fluctuations from event-to-event. The gold standard method would entail a track-by-track analysis of the particle composition, but this is not feasible with the current statistics nor current species separation power in our detectors. However, future detectors may have the capability to perform such an analysis.

A complementary study that could shed light on the source of strangeness enhancements would be the kaon to pion ratio in constituents from reconstructed jets in heavy-ion collisions. This has yet to be measured and could provide a more direct comparison to the results presented here. If strangeness from jet-medium interactions is distributed to wider angles, a measurement of the R-dependence of the kaon to pion ratio could reveal this. Furthermore, one could investigate the K_0^s to π^0 ratio in jets. This measurement has the benefit of being less sensitive to PID and non-combinatorial backgrounds, although it comes with its own challenges.

We believe that our measurements warrant further investigation into strangeness enhancement in jets as a signature of jet modification. The strangeness enhancement

seen at, and exceeding, the levels in the QGP itself, suggests that jet hadrochemistry is modified by collisional and radiative interactions while traversing the QGP, while the lack of baryon enhancement may suggest that baryon production via recombination is suppressed. Future comparisons to simulation will be necessary to understand the mechanisms driving these results.

Bibliography

- [1] John Adams et al. Experimental and theoretical challenges in the search for the quark gluon plasma: The STAR Collaboration’s critical assessment of the evidence from RHIC collisions. *Nucl. Phys. A*, 757:102–183, 2005. [1](#), [15](#)
- [2] K. Adcox et al. Formation of dense partonic matter in relativistic nucleus-nucleus collisions at RHIC: Experimental evaluation by the PHENIX collaboration. *Nucl. Phys. A*, 757:184–283, 2005. [1](#)
- [3] I. Arsene et al. Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment. *Nucl. Phys. A*, 757:1–27, 2005. [1](#)
- [4] Ulrich Heinz and Raimond Snellings. Collective flow and viscosity in relativistic heavy-ion collisions. *Ann. Rev. Nucl. Part. Sci.*, 63:123–151, 2013. [1](#)
- [5] Miklos Gyulassy and Michael Plumer. Jet Quenching in Dense Matter. *Phys. Lett. B*, 243:432–438, 1990. [1](#)
- [6] Jaroslav Adam et al. Measurement of jet suppression in central Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. *Phys. Lett. B*, 746:1–14, 2015. [1](#), [15](#)
- [7] M. Aaboud et al. Measurement of the nuclear modification factor for inclusive jets in pb+pb collisions at $\sqrt{s_{\text{NN}}}=5.02$ tev with the atlas detector. *Physics Letters B*, 790:108–128, 2019. [1](#), [22](#)

- [8] Shreyasi Acharya et al. Production of charged pions, kaons, and (anti-)protons in Pb-Pb and inelastic pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. C*, 101(4):044907, 2020. [1](#), [75](#), [81](#), [82](#), [83](#), [84](#), [87](#)
- [9] R. J. Fries, Berndt Muller, C. Nonaka, and S. A. Bass. Hadronization in heavy ion collisions: Recombination and fragmentation of partons. *Phys. Rev. Lett.*, 90:202303, 2003. [1](#), [14](#)
- [10] Gabriel Dale-Gau. Baryon-to-Meson Ratios in Jets from Au+Au and $p+p$ Collisions at $\sqrt{s_{NN}} = 200$ GeV. *PoS, HardProbes2023*:173, 2024. [2](#), [21](#), [26](#)
- [11] Vít Kučera and (for the ALICE Collaboration). Production of strange particles in charged jets in pb–pb and p–pb collisions measured with alice. *Journal of Physics: Conference Series*, 612(1):012013, apr 2015. [2](#), [25](#), [27](#)
- [12] Jiaxu Zuo and (for the STAR Collaboration). Baryon to meson ratios on the near and away side of jets and their centrality dependence at star. *Journal of Physics G: Nuclear and Particle Physics*, 35(4):044027, mar 2008. [2](#), [25](#), [28](#), [84](#)
- [13] B. Abelev et al. Near-side azimuthal and pseudorapidity correlations using neutral strange baryons and mesons in d+Au, Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. C*, 94(1):014910, 2016. [2](#), [29](#)
- [14] A. Dávila. Proton/pion ratios in $\Delta\phi$ with respect to a jet in $\sqrt{s_{NN}}=200$ GeV Au + Au collisions at star. *Nuclear Physics A*, 910-911:310–313, 2013. Hard Probes 2012. [2](#), [25](#), [30](#), [84](#)
- [15] P. Sorensen. Identified particle spectra and jet interactions with the medium. *Nuclear Physics A*, 774:247–256, 2006. QUARK MATTER 2005. [2](#), [25](#)
- [16] F. Bissey, F-G. Cao, A. R. Kitson, A. I. Signal, D. B. Leinweber, B. G. Lasscock, and A. G. Williams. Gluon flux-tube distribution and linear confinement in baryons. *Phys. Rev. D*, 76:114512, 2007. [2](#)

- [17] David J. Gross and Frank Wilczek. Ultraviolet behavior of non-abelian gauge theories. *Phys. Rev. Lett.*, 30:1343–1346, Jun 1973. [2](#)
- [18] R. Hagedorn. Statistical thermodynamics of strong interactions at high-energies. *Nuovo Cim. Suppl.*, 3:147–186, 1965. [4](#)
- [19] N. Cabibbo and G. Parisi. Exponential hadronic spectrum and quark liberation. *Physics Letters B*, 59(1):67–69, 1975. [4](#)
- [20] Yasuyuki Akiba et al. The Hot QCD White Paper: Exploring the Phases of QCD at RHIC and the LHC. 2 2015. [4](#)
- [21] A. Bazavov et al. Chiral crossover in qcd at zero and non-zero chemical potentials. *Physics Letters B*, 795:15–21, 2019. [4](#)
- [22] A. Bazavov et al. Equation of state in (2+1)-flavor QCD. *Phys. Rev. D*, 90:094503, 2014. [4](#)
- [23] Jaroslav Adam et al. Measurement of transverse energy at midrapidity in Pb-Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV. *Phys. Rev. C*, 94(3):034903, 2016. [4](#)
- [24] Deeptak Biswas. Centrality dependence of chemical freeze-out parameters and strangeness equilibration in RHIC and LHC energies. *Adv. High Energy Phys.*, 2021:6611394, 2021. [4](#), [87](#)
- [25] Jonah E Bernhard, J Scott Moreland, and Steffen A Bass. Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma. *Nature Physics*, 15(11):1113–1117, 2019. [4](#)
- [26] Rajeev S. Bhalerao. Relativistic heavy-ion collisions. In *1st Asia-Europe-Pacific School of High-Energy Physics*, pages 219–239, 2014. [3](#)
- [27] Reinhard Stock. *Relativistic Nucleus-Nucleus Collisions and the QCD Matter Phase Diagram*, pages 311–453. Springer International Publishing, Cham, 2020. [6](#)

- [28] J. Scott Moreland, Jonah E. Bernhard, and Steffen A. Bass. Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions. *Phys. Rev. C*, 92:011901, Jul 2015. [7](#)
- [29] Michael L. Miller, Klaus Reygers, Stephen J. Sanders, and Peter Steinberg. Glauber modeling in high energy nuclear collisions. *Ann. Rev. Nucl. Part. Sci.*, 57:205–243, 2007. [7](#)
- [30] Jacob J. Ethier and Emanuele R. Nocera. Parton Distributions in Nucleons and Nuclei. *Ann. Rev. Nucl. Part. Sci.*, 70:43–76, 2020. [7](#), [10](#)
- [31] A. Accardi et al. Electron Ion Collider: The Next QCD Frontier: Understanding the glue that binds us all. *Eur. Phys. J. A*, 52(9):268, 2016. [7](#)
- [32] John W. Harris and Berndt Muller. The Search for the quark - gluon plasma. *Ann. Rev. Nucl. Part. Sci.*, 46:71–107, 1996. [11](#)
- [33] Barbara Betz. Jet propagation and mach-cone formation in (3+1)-dimensional ideal hydrodynamics. 10 2009. [8](#)
- [34] Jingkai Wang et al. Using the optical glauber monte carlo model to calculate $r_{AA}/i_{ij}/sub_{ij}$ related results produced by the atlas collaboration. *Natural science*, 12(03):65–73, 2020. [9](#)
- [35] Peter F. Kolb and Ulrich W. Heinz. Hydrodynamic description of ultrarelativistic heavy ion collisions. pages 634–714, 5 2003. [11](#)
- [36] Ulrich Heinz and Raimond Snellings. Collective flow and viscosity in relativistic heavy-ion collisions. *Ann. Rev. Nucl. Part. Sci.*, 63:123–151, 2013. [11](#)
- [37] S. Voloshin and Y. Zhang. Flow study in relativistic nuclear collisions by Fourier expansion of Azimuthal particle distributions. *Z. Phys. C*, 70:665–672, 1996. [11](#)
- [38] K Aamodt et al. Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV. *Phys. Rev. Lett.*, 105:252302, 2010. [11](#)

- [39] Shreyasi Acharya et al. Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. *JHEP*, 05:243, 2023. [11](#), [12](#)
- [40] Jaroslav Adam et al. Azimuthal anisotropy of charged jet production in $\sqrt{s_{\text{NN}}} = 2.76$ TeV Pb–Pb collisions. *Phys. Lett. B*, 753:511–525, 2016. [11](#)
- [41] A. Adare et al. Scaling properties of azimuthal anisotropy in Au+Au and Cu+Cu collisions at $s(\text{NN}) = 200$ -GeV. *Phys. Rev. Lett.*, 98:162301, 2007. [11](#), [13](#)
- [42] Natasha Sharma, Tony Perez, Andy Castro, Lokesh Kumar, and Christine Nattrass. Methods for separation of deuterons produced in the medium and in jets in high energy collisions. *Phys. Rev. C*, 98(1):014914, 2018. [14](#)
- [43] J. Adam et al. Production of light nuclei and anti-nuclei in pp and pb–pb collisions at energies available at the cern large hadron collider. *Phys. Rev. C*, 93:024917, Feb 2016. [15](#)
- [44] Zoltan Fodor and Sandor D. Katz. Critical point of qcd at finite t and μ , lattice results for physical quark masses. *Journal of High Energy Physics*, 2004(04):050, may 2004. [15](#)
- [45] Tom Kaufmann, Asmita Mukherjee, and Werner Vogelsang. Hadron Fragmentation Inside Jets in Hadronic Collisions. *Phys. Rev. D*, 92(5):054015, 2015. [Erratum: Phys.Rev.D 101, 079901 (2020)]. [15](#)
- [46] Zhong-Bo Kang, Felix Ringer, and Ivan Vitev. The semi-inclusive jet function in SCET and small radius resummation for inclusive jet production. *JHEP*, 10:125, 2016. [15](#)
- [47] Lin Dai, Chul Kim, and Adam K. Leibovich. Fragmentation of a Jet with Small Radius. *Phys. Rev. D*, 94(11):114023, 2016. [15](#)

- [48] Jian-Wei Qiu, Felix Ringer, Nobuo Sato, and Pia Zurita. Qcd factorization and universality of jet cross sections in heavy-ion collisions. *Nuclear Physics A*, 1005:121853, 2021. The 28th International Conference on Ultra-relativistic Nucleus-Nucleus Collisions: Quark Matter 2019. [15](#), [16](#)
- [49] John E. Huth et al. Toward a standardization of jet definitions. In *1990 DPF Summer Study on High-energy Physics: Research Directions for the Decade (Snowmass 90)*, page 0134136, 12 1990. [17](#)
- [50] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. The anti- k_t jet clustering algorithm. *JHEP*, 04:063, 2008. [17](#), [19](#)
- [51] S. Catani et al. Longitudinally invariant K_t clustering algorithms for hadron hadron collisions. *Nucl. Phys. B*, 406:187–224, 1993. [17](#)
- [52] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. FastJet User Manual. *Eur. Phys. J. C*, 72:1896, 2012. [17](#), [56](#)
- [53] Stephen D. Ellis and Davison E. Soper. Successive combination jet algorithm for hadron collisions. *Phys. Rev. D*, 48:3160–3166, Oct 1993. [17](#)
- [54] Gavin P. Salam and Gregory Soyez. A Practical Seedless Infrared-Safe Cone jet algorithm. *JHEP*, 05:086, 2007. [17](#)
- [55] Betty Abelev et al. Measurement of Event Background Fluctuations for Charged Particle Jet Reconstruction in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *JHEP*, 03:053, 2012. [19](#)
- [56] Megan Connors, Christine Nattrass, Rosi Reed, and Sevil Salur. Jet measurements in heavy ion physics. *Rev. Mod. Phys.*, 90:025005, 2018. [19](#)
- [57] Patrick Steffanic, Charles Hughes, and Christine Nattrass. Separating signal from combinatorial jets in a high-background environment. *Phys. Rev. C*, 108(2):024909, 2023. [19](#)

- [58] Chathuranga Sirimanna, Ismail Soudi, Gojko Vujanovic, Wen-Jing Xing, Shanshan Cao, and Abhijit Majumder. Quenching jets increases their flavor. *Phys. Rev. C*, 108:014911, Jul 2023. [20](#), [87](#)
- [59] Marguerite Belt Tonjes. Inclusive jet and charged hadron nuclear modification factors in PbPb collisions at 2.76 TeV with CMS. *Nucl. Phys. A*, 904-905:713c–716c, 2013. [20](#)
- [60] B. Abelev et al. Measurement of charged jet suppression in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *JHEP*, 03:013, 2014. [20](#)
- [61] Shreyasi Acharya et al. Measurements of inclusive jet spectra in pp and central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Rev. C*, 101(3):034911, 2020. [20](#)
- [62] Jaroslav Adam et al. Measurement of jet suppression in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B*, 746:1–14, 2015. [20](#)
- [63] Shreyasi Acharya et al. Measurement of the radius dependence of charged-particle jet suppression in Pb–Pb collisions at sNN=5.02TeV. *Phys. Lett. B*, 849:138412, 2024. [20](#), [23](#)
- [64] K. Aamodt et al. Suppression of Charged Particle Production at Large Transverse Momentum in Central Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B*, 696:30–39, 2011. [21](#)
- [65] S. Acharya et al. Transverse momentum spectra and nuclear modification factors of charged particles in pp, p-Pb and Pb-Pb collisions at the LHC. *JHEP*, 11:013, 2018. [21](#)
- [66] Betty Abelev et al. Centrality Dependence of Charged Particle Production at Large Transverse Momentum in Pb–Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B*, 720:52–62, 2013. [21](#)

- [67] Betty Bezverkhny Abelev et al. Production of charged pions, kaons and protons at large transverse momenta in pp and Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Lett. B*, 736:196–207, 2014. [21](#)
- [68] Nicolò Jacazio. Production of identified charged hadrons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Nucl. Phys. A*, 967:421–424, 2017. [21](#)
- [69] Jaroslav Adam et al. Centrality dependence of the nuclear modification factor of charged pions, kaons, and protons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. *Phys. Rev. C*, 93(3):034913, 2016. [21](#), [24](#)
- [70] A. Adare et al. Cold-Nuclear-Matter Effects on Heavy-Quark Production in $d+Au$ Collisions at $\sqrt{s_{NN}}=200$ GeV. *Phys. Rev. Lett.*, 109:242301, Dec 2012. [21](#)
- [71] A. Adare et al. Heavy-flavor electron-muon correlations in $p + p$ and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ gev. *Phys. Rev. C*, 89:034915, Mar 2014. [21](#)
- [72] A. Adare et al. Nuclear modification of ψ' , χ_c , and j/ψ production in $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. *Phys. Rev. Lett.*, 111:202301, Nov 2013. [21](#)
- [73] B. I. Abelev et al. Inclusive π^0 , η , and direct photon production at high transverse momentum in $p + p$ and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ gev. *Phys. Rev. C*, 81:064904, Jun 2010. [21](#)
- [74] S. S. Adler et al. Centrality dependence of π^0 and η production at large transverse momentum in $\sqrt{s_{NN}} = 200$ GeV $d + Au$ collisions. *Phys. Rev. Lett.*, 98:172302, Apr 2007. [21](#)
- [75] Measurement of charged particle spectra in pp collisions and nuclear modification factor R_{pPb} at $\sqrt{s_{NN}} = 5.02$ TeV with the ATLAS detector at the LHC. Technical report, CERN, Geneva, 2016. All figures including auxiliary figures are available at <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2016-108>. [21](#)

- [76] B. Abelev et al. Transverse momentum distribution and nuclear modification factor of charged particles in p +Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV. *Phys. Rev. Lett.*, 110:082302, Feb 2013. [21](#)
- [77] Vardan Khachatryan et al. Nuclear Effects on the Transverse Momentum Spectra of Charged Particles in pPb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Eur. Phys. J. C*, 75(5):237, 2015. [21](#)
- [78] Vardan Khachatryan et al. Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *JHEP*, 04:039, 2017. [21](#)
- [79] Jaroslav Adam et al. Measurement of charged jet production cross sections and nuclear modification in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Phys. Lett. B*, 749:68–81, 2015. [21](#)
- [80] Vardan Khachatryan et al. Measurement of inclusive jet production and nuclear modifications in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. *Eur. Phys. J. C*, 76(7):372, 2016. [21](#)
- [81] Esma Mobs. The CERN accelerator complex in 2019. Complexe des accélérateurs du CERN en 2019. 2019. General Photo. [33](#)
- [82] Y. Zoccarato et al. Front end electronics and first results of the ALICE V0 detector. *Nucl. Instrum. Meth. A*, 626-627:90–96, 2011. [36](#)
- [83] A. M. Poskanzer and S. A. Voloshin. Methods for analyzing anisotropic flow in relativistic nuclear collisions. *Phys. Rev. C*, 58:1671–1678, Sep 1998. [40](#), [57](#)
- [84] K Aamodt et al. The ALICE experiment at the CERN LHC. A Large Ion Collider Experiment. *JINST*, 3:S08002, 2008. Also published by CERN Geneva in 2010. [41](#), [42](#), [43](#), [44](#)

- [85] Raymond Ehlers. *Jet-Hadron Correlations Measured in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE*. PhD thesis, Yale U., 2019. Presented 10 Oct 2019. [52](#), [63](#)
- [86] Charles P. Hughes. *Measurement of Jet Constituent Yields in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV Using the ALICE Detector*. PhD thesis, Tennessee U., 2022. [52](#), [54](#), [55](#), [56](#)
- [87] Miklos Gyulassy and Xin-Nian Wang. HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions. *Comput. Phys. Commun.*, 83:307, 1994. [54](#)
- [88] Xin-Nian Wang and Miklos Gyulassy. hijing: A monte carlo model for multiple jet production in pp, pA, and AA collisions. *Phys. Rev. D*, 44:3501–3516, Dec 1991. [54](#)
- [89] J. Barrette et al. Proton and pion production relative to the reaction plane in au + au collisions at 11a gev/c. *Phys. Rev. C*, 56:3254–3264, Dec 1997. [57](#)
- [90] Natasha Sharma et al. Background subtraction methods for precision measurements of di-hadron and jet-hadron correlations in heavy ion collisions. *Phys. Rev. C*, 93:044915, Apr 2016. [64](#)
- [91] Christine Nattrass and Takahito Todoroki. Event plane dependence of the flow modulated background in dihadron and jet-hadron correlations in heavy ion collisions. *Phys. Rev. C*, 97:054911, May 2018. [64](#), [65](#)
- [92] Pauli Virtanen et al. SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python. *Nature Methods*, 17:261–272, 2020. [65](#)
- [93] Elena Botta. Particle identification performance at ALICE. Particle identification performance at ALICE. Technical report, 2017. 6 pages, 5 figures, Proceeding of the Fifth Annual Conference on Large Hadron Collider Physics, May 15-20, 2017, Shanghai, Cina. [67](#)

- [94] Shreyasi Acharya et al. Anisotropic flow and flow fluctuations of identified hadrons in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. *JHEP*, 05:243, 2023. [75](#)
- [95] P. Levai, G. Papp, George I. Fai, and M. Gyulassy. Kaon and pion ratio probes of jet quenching in nuclear collisions. *Acta Phys. Hung. A*, 27:459–468, 2006. [87](#)

Appendix A

Results

A.1 Central

Near side signal

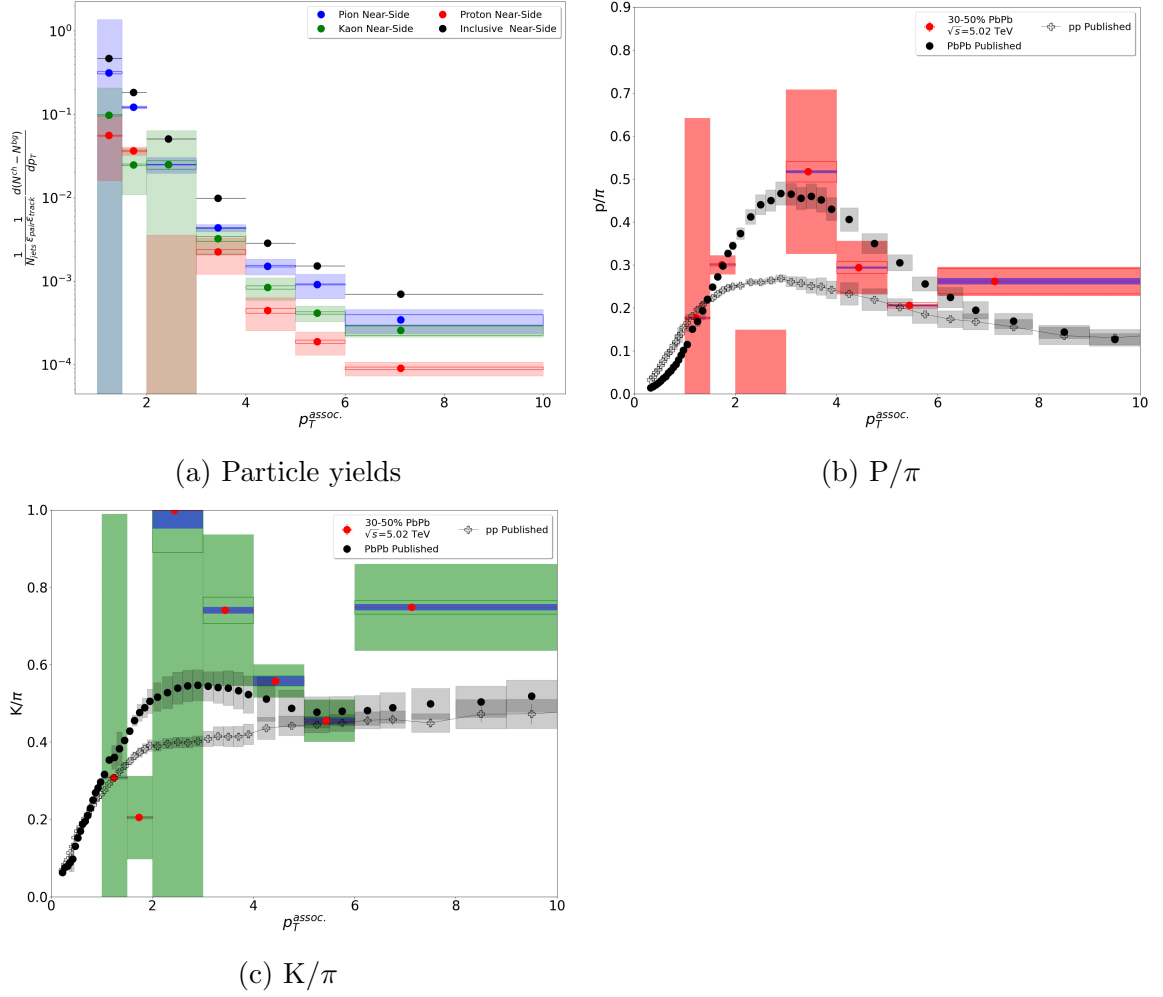
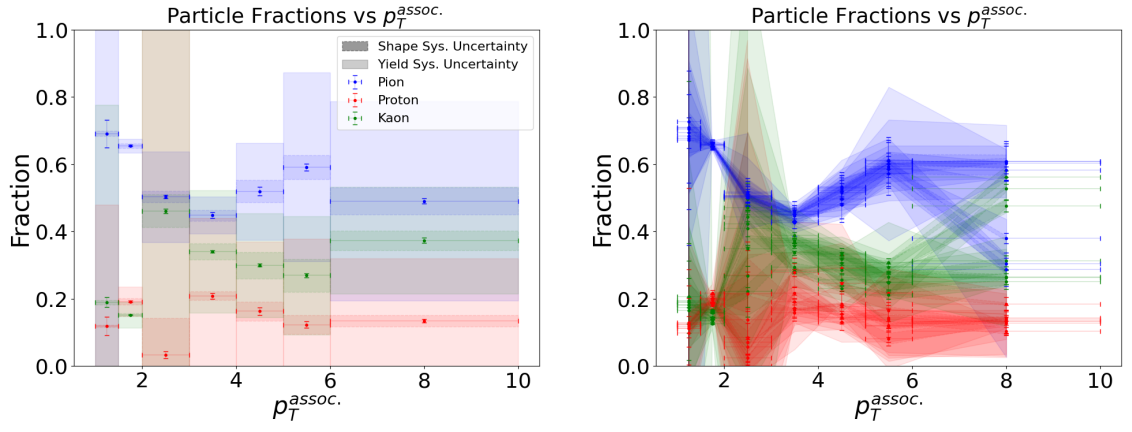


Figure A.1: 0-10% central collisions using jets with $20 \text{ GeV}/c < p_T^{\text{jet}} < 40 \text{ GeV}/c$ in the near-side signal region.



(a) Particle fractions averaged over 8 independent data splits. (b) Particle fractions for all 8 independent data splits.

Figure A.2: 0-10% central collisions using jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$ in the near-side signal region.

Away side signal

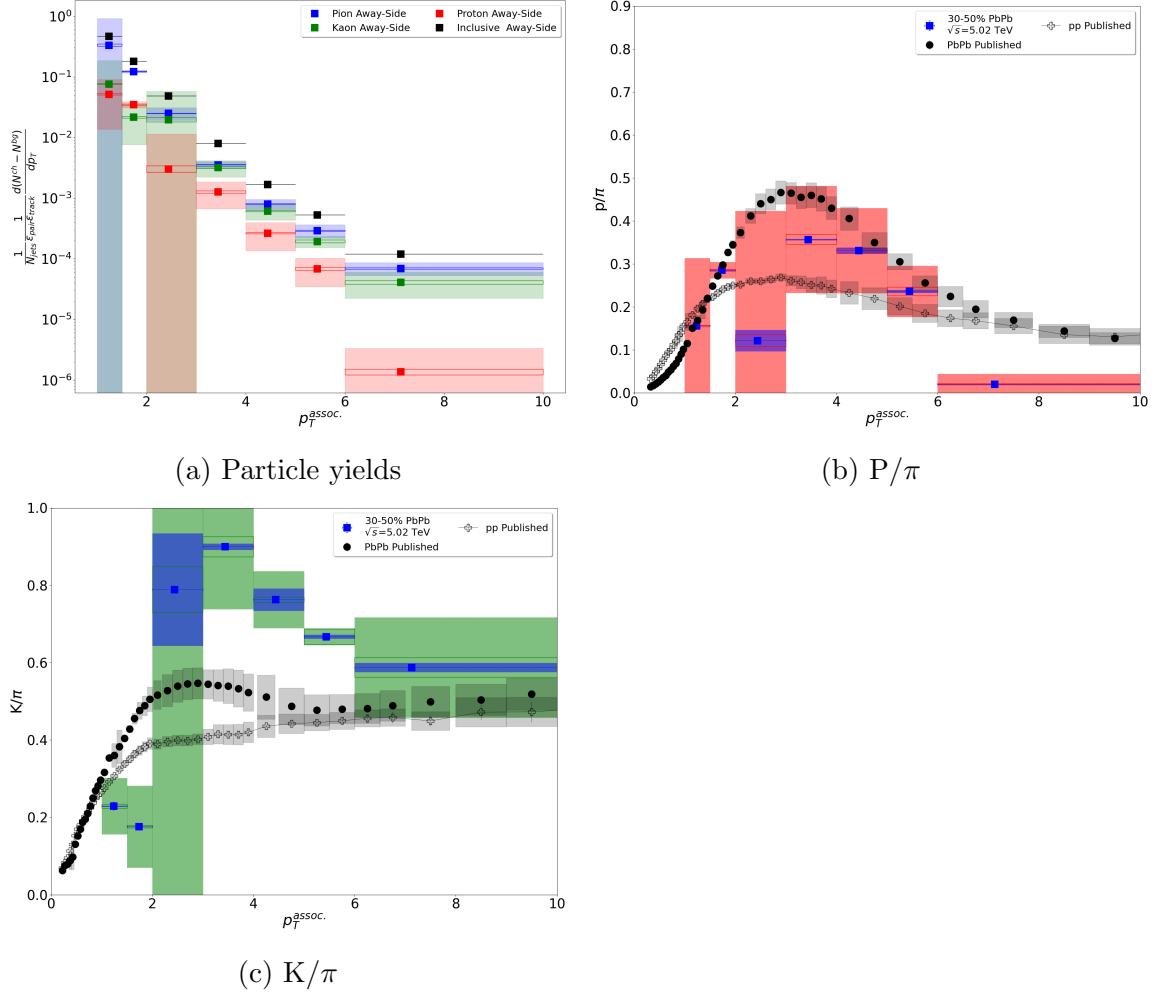
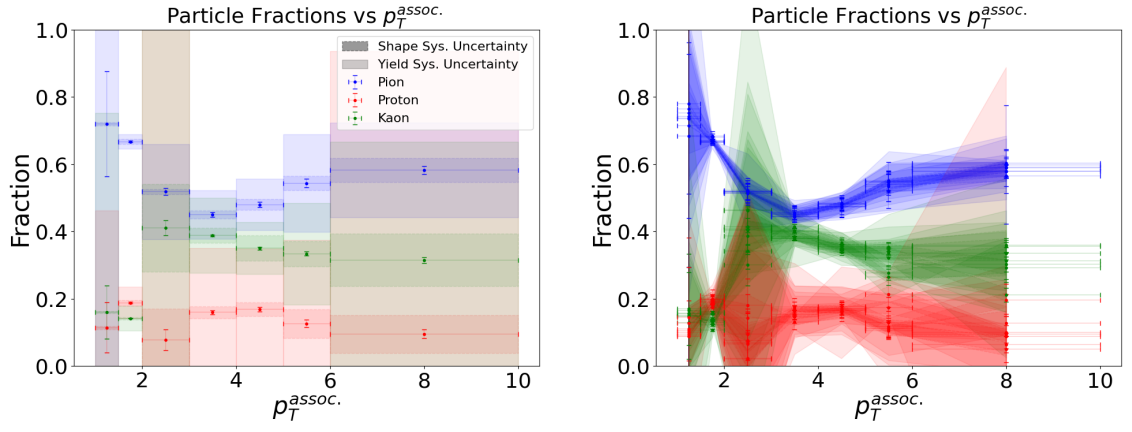


Figure A.3: 0-10% central collisions using jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$ in the away-side signal region.



(a) Particle fractions averaged over 8 independent data splits. (b) Particle fractions for all 8 independent data splits.

Figure A.4: 0-10% central collisions using jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$ in the away-side signal region.

A.2 Semicentral

Near side signal

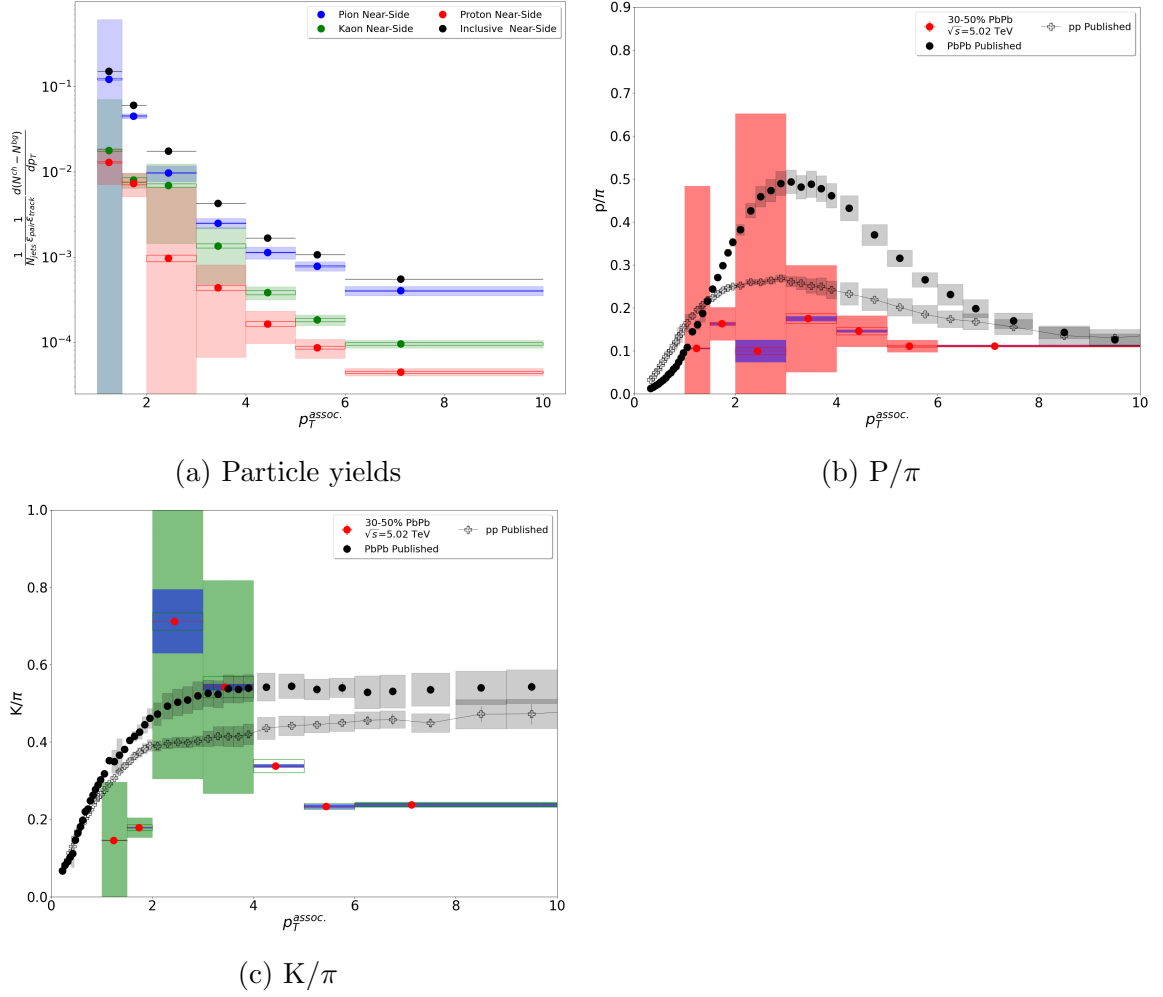
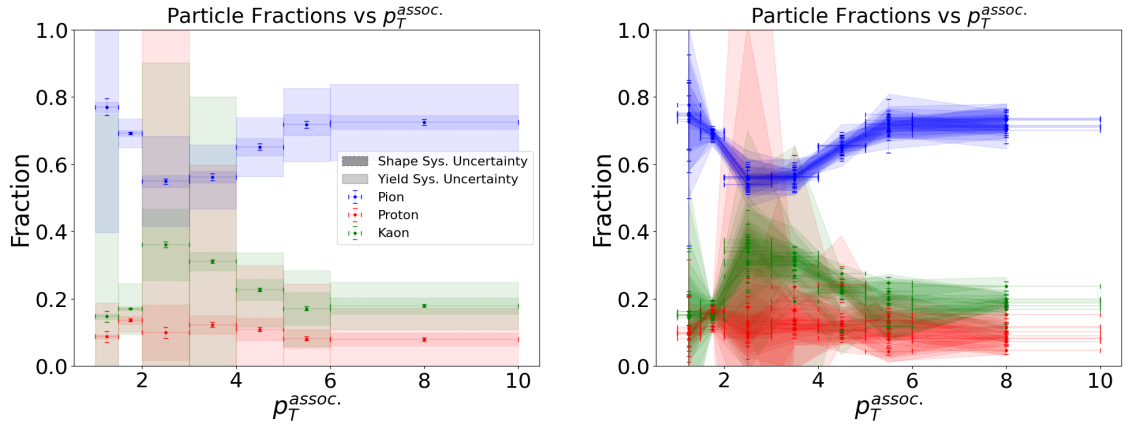


Figure A.5: 30-50% central collisions using jets with $20 \text{ GeV}/c < p_T^{\text{jet}} < 40 \text{ GeV}/c$ in the near-side signal region.



(a) Particle fractions averaged over 8 independent data splits.

(b) Particle fractions for all 8 independent data splits.

Figure A.6: 30-50% central collisions using jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$ in the near-side signal region.

Away side signal

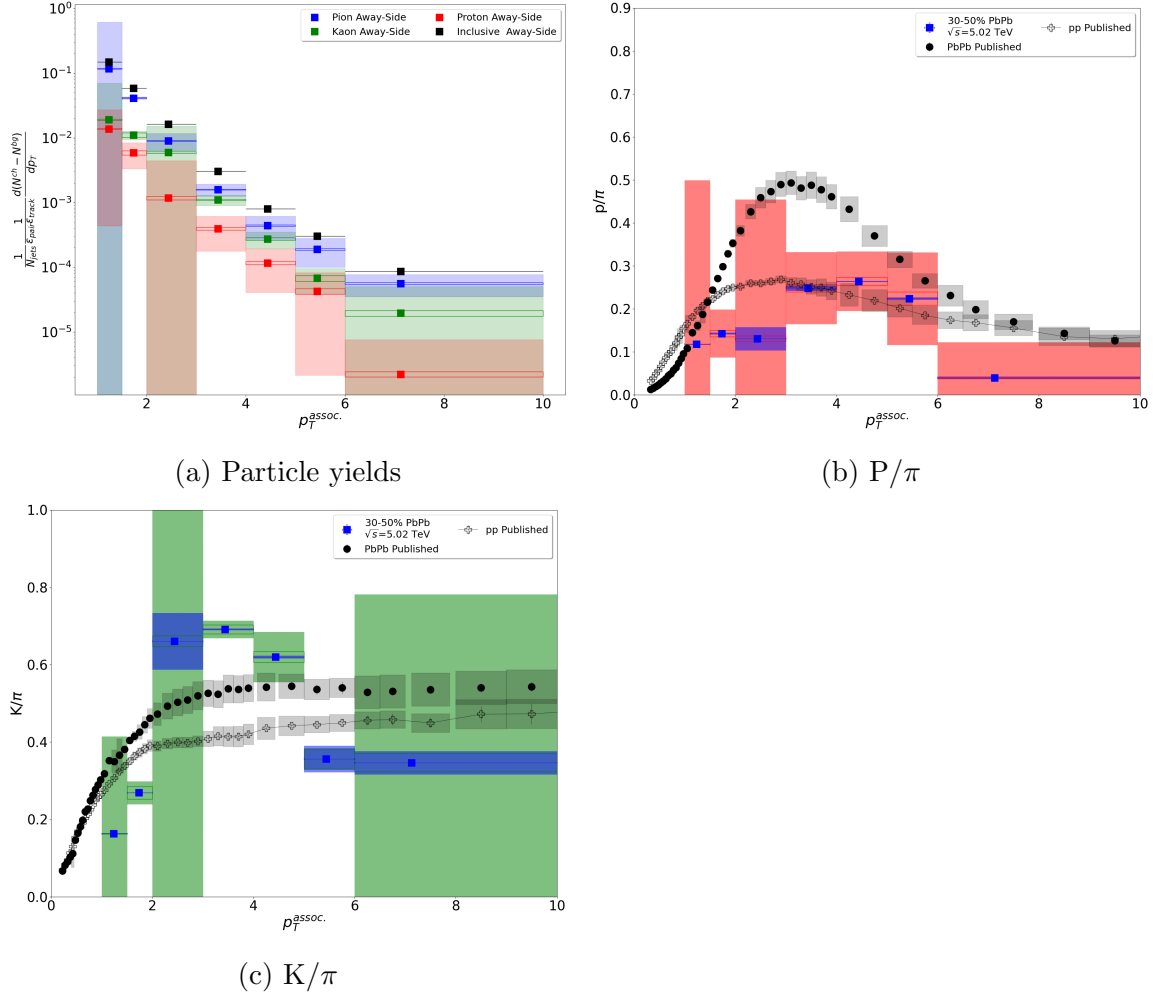
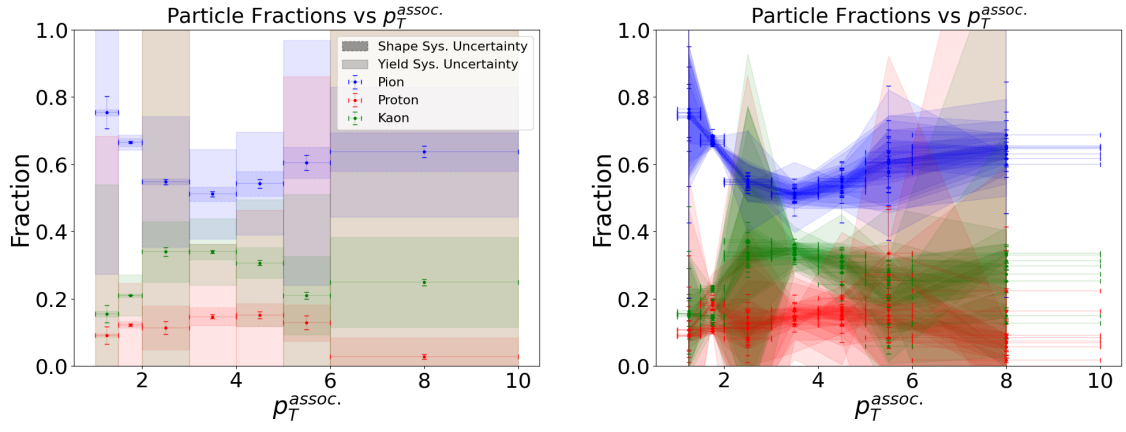


Figure A.7: 30-50% central collisions using jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$ in the away-side signal region.



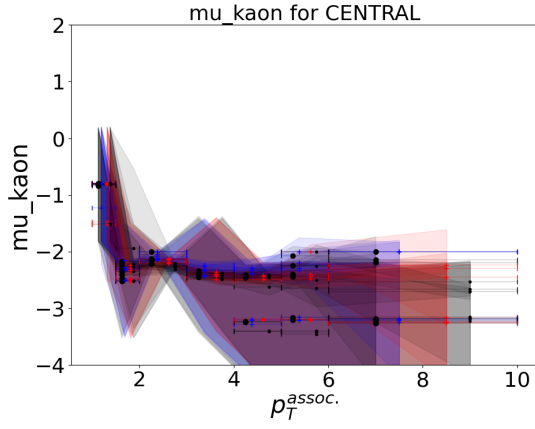
(a) Particle fractions averaged over 8 independent data splits. (b) Particle fractions for all 8 independent data splits.

Figure A.8: 30-50% central collisions using jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$ in the away-side signal region.

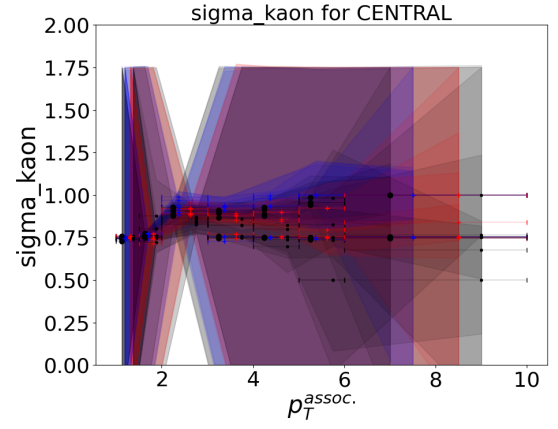
Appendix B

PID Fits

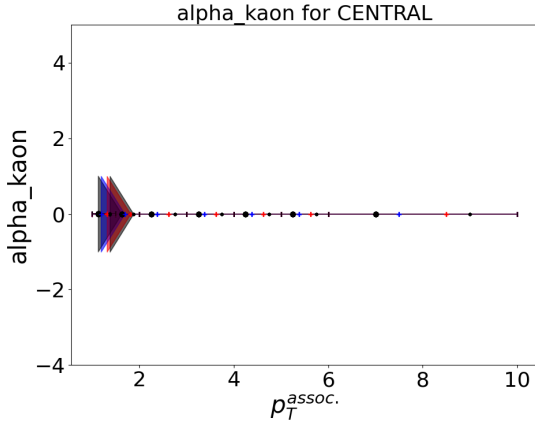
B.1 Central



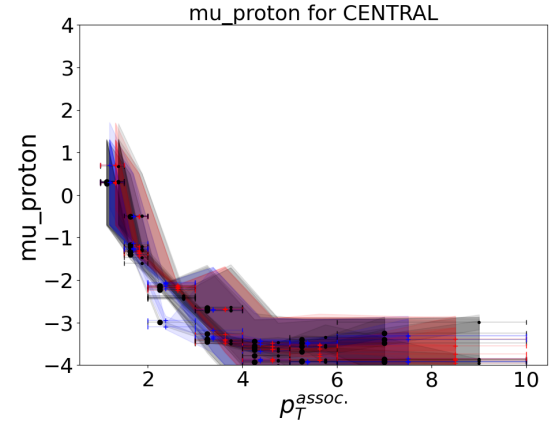
(a) μ of the Kaon distribution.



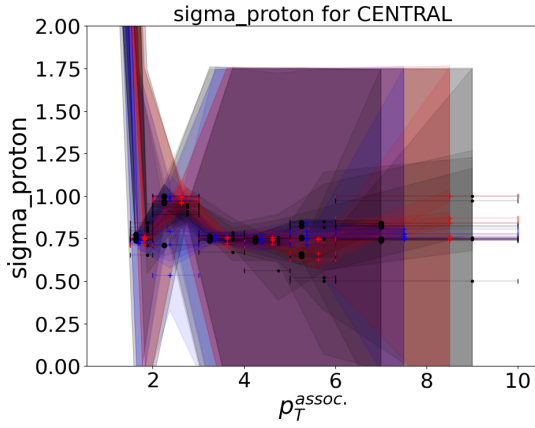
(b) σ of the Kaon distribution.



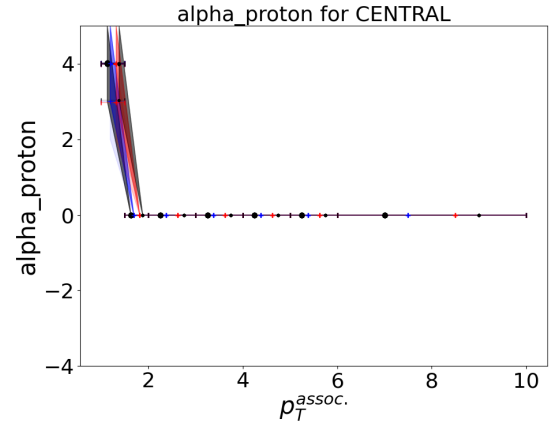
(c) α of the Kaon distribution.



(d) μ of the Proton distribution.



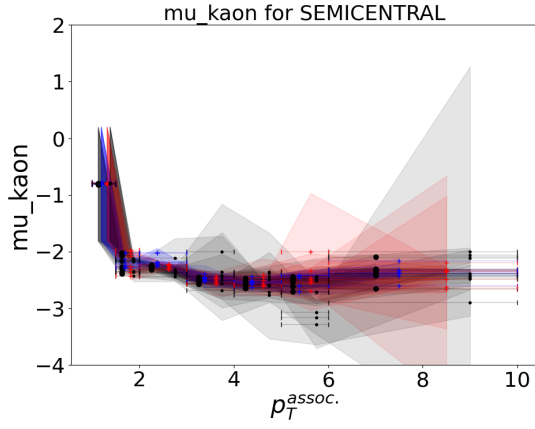
(e) σ of the Proton distribution.



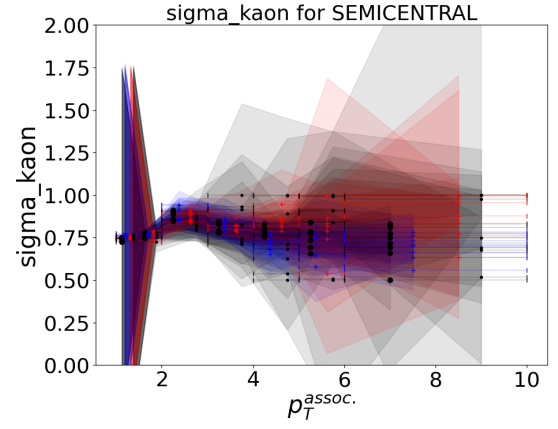
(f) α of the Proton distribution.

Figure B.1: 0–10% central collisions for jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$.

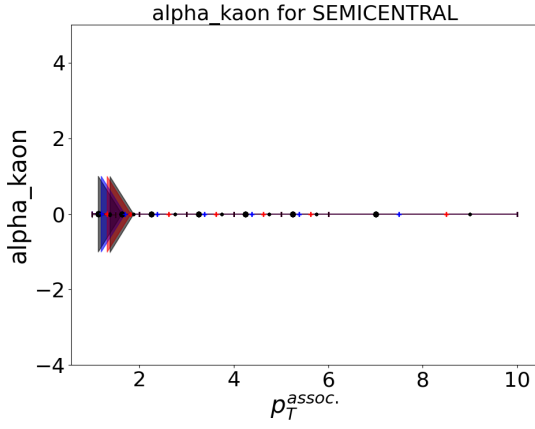
B.2 Semicentral



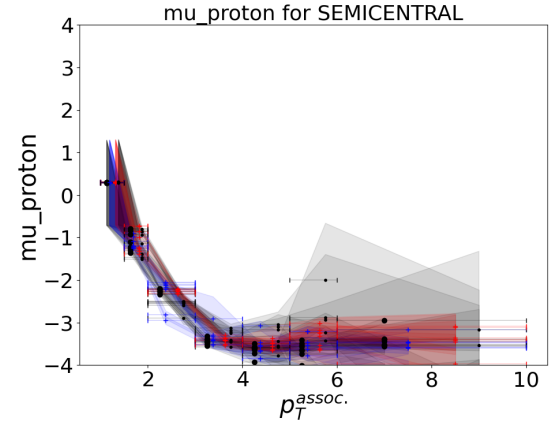
(a) μ of the Kaon distribution.



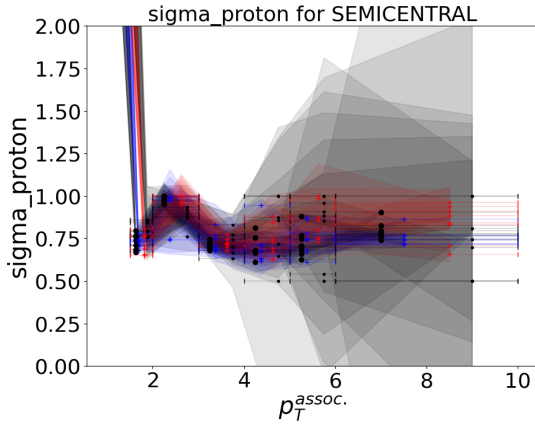
(b) σ of the Kaon distribution.



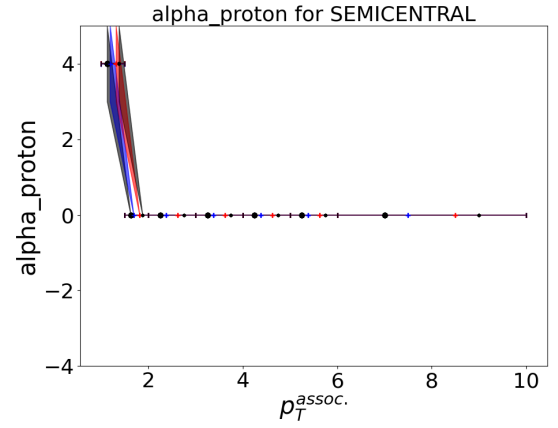
(c) α of the Kaon distribution.



(d) μ of the Proton distribution.



(e) σ of the Proton distribution.



(f) α of the Proton distribution.

Figure B.2: 30–50% central collisions for jets with $20 \text{ GeV}/c < p_T^{jet} < 40 \text{ GeV}/c$.

Vita

Patrick Steffanic was born in October of 1994 and was raised in the small railroad town of Portola, CA nestled in the beautiful Sierra Nevada mountains. He attended Portola High School where he was set on a quest by Mr. Womack to, very specifically, "double major in math and physics, go get your PhD in physics, then do whatever you want to do!" He attended Cal Poly in San Luis Obispo, the happiest city in America, where he did get that double major in math and physics, as well as doing research in collaboration with CERN. He then went on to the University of Tennessee, Knoxville as a recipient of the Tennessee Graduate Research Excellence Fellowship under the group of Christine Nattrass. He is still figuring out the "do whatever you want" part, and looks forward to an exciting future!